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SEMINAR ON ELECTROSTATICS AND FINE PARTICLES--SEPTEMBER 1973

D. C. Drehmel

National Environmental Research Center
Research Triangle Park, North Carolina

August 1974

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The report gives results of a 2-day seminar on the application of electrostatics to fine particle control. The first three papers discuss the use of charged droplets for scrubbing fine particles out of an effluent gas stream. Later the same day, an open panel discussion was held on charged droplet scrubbing. Electrostatic phenomena in fiber filters and in electrostatic precipitators were subjects of other papers during the seminar. These led to an open discussion of new electrostatic concepts for the abatement of fine particulate emissions. Papers on aerosol generation and measurement were also part of the program.

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SEMINAR
ON ELECTROSTATICS
AND FINE PARTICLES
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Control Systems Laboratory
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August 1974

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FOREWORD

The U. S. Environmental Protection Agency, through the Office of Research and Development's Control Systems Laboratory, sponsored a Seminar on Electrostatics and Fine Particles. The Seminar was held at EPA's National Environmental Research Center (NERC) at Research Triangle Park, N. C., September 6 and 7, 1973.

The seminar, consisting of two sessions, got underway Thursday morning, September 6, with an official welcome by A. B. Craig, Chief of the Control Systems Laboratory's Particulate and Chemical Processes Branch. Introductory remarks by J. H. Abbott, Chief of the Particulate Technology Section, led into the first session.

The Thursday session, chaired by D. C. Drehmel, consisted of four presentations (each followed by a question and answer period) and a panel discussion. The presentations were by: J. Melcher of MIT, C. Lear of TRW, M. Pilat of the University of Washington, and A. Postma of Battelle Northwest. The four, joined by Moderator Drehmel and G. Penney of Carnegie-Mellon University, composed the session-closing panel.

The second session (Friday) was chaired by EPA's L. E. Sparks. It, too, consisted of four presentations; however, this session concluded with an open discussion moderated by J. H. Abbott. Making presentations during the Friday session were G. Nichols of Southern Research Institute, G. Penney, J. McCain, also of Southern Research Institute, and B. Linsky of West Virginia University. Each presentation was followed by a question and answer period.

This document is, in essence, minutes of the Seminar. All presentations were taped and the tapes transcribed, with little editing, to record the material presented by the speakers. Unfortunately, this document does not include visual material (slides) presented by the speakers.

Since this document is a transcript, the wording is often not exact and must be read conversationally. The original tapes were frequently ambiguous or confusing. In these cases, the presenters or the editors supplied additional information or replaced text with more formal wording. The papers contained herein are not formal papers and must be used only as minutes of a working seminar. Speakers were not required to present a preprint in order that their information as given would be the most recent at that time.

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Presentation No. 1

INVESTIGATION OF SYSTEMS OF CHARGED PARTICLES AND ELECTRIC FIELDS FOR THE REMOVAL OF SUBMICRON PARTICULATE

by

Dr. J. Melcher and K. Sachar
Massachusetts Institute of Technology

Drehmel: At this time I would like to introduce Dr. Melcher. Dr. Melcher has been under contract with EPA for over a year and a half in the area of charged droplet scrubbing and has been one of the driving forces in developing this technique for fine particulate control. He has a B. S. in Electrical Engineering and a M. S. in Nuclear Engineering from Iowa State University; he has a Ph.D. in Electrical Engineering from MIT. Since joining the MIT faculty in 1962, Dr. Melcher's research and consulting interests have centered around continuum electromechanics with major emphasis on electrohydrodynamics, continuum feedback control and energy conversion. He is the author of more than 35 journal publications and has written several publications including a book on electromechanical dynamics. He has also won several awards. At this time I would like to ask Dr. Melcher to give us his comments on the work he has done for the past year and a half.

Melcher: It is quite an honor to start this off because I have the opportunity to give you my view of things and perhaps get you to adopt a few of my viewpoints at the very outset. I will be making this presentation jointly with Ken Sachar, a graduate student at MIT who has been working on this project.

First of all, I will put down some basic statements that in general have to do with the use of charged droplets for collecting particles. This will make possible an overview of the real engineering possibilities and limitations inherent to the use of charged drops and serve as a guide in determining where we ought to be going.

To begin with, I am going to talk a moment in theoretical terms. And what I would like to do is get you to adopt the viewpoint that what governs the collection of small charged particles on large ones is a set of time constants. Some of you have seen these before, but let me remind you. We call them τ^*, τ_d and τ_R. They are all measured in seconds. When we talk about the particles to be collected, I am going to attribute to them a size a, a mobility b and a number density per unit volume n. When we talk about the drops, I am going to attribute to them a radius R, a mobility B and a number density N. Now I will identify three time constants that determine how successful you will be in collecting the particulate by this mechanism. The first is a time, $\tau^* = \varepsilon_0/nqb$.

A second time constant, ε_0/NQb describes the interaction of the submicron or the small particles with the big ones. It is based on the charge density of the big particles and the mobility of the small ones--the ones to be collected. We finally have a third time constant which is the analog of the time τ^* for the small particles. This time is $\tau_R = \varepsilon_0/NQB$. The constraints that you have in making the big particles collect little ones are very much tied up in the typical times, because they describe not only the rate at which big particles collect little ones but also the rate at which you lose big particles due to their own fields.

I would like to distinguish first of all between processes by which particles come together through microfields that exist between the particles and macrofield processes where (due to the charge on the particles) they tend to go to walls. Supposing that I had a box--I'll make it plainer so that we only have one critical dimension, a certain width L and fill it up with particles having this little charge q. (We are going to hear talk later on a self precipitation type device and you can see that this is what I have made.) We fill this box up with particles all having the same sign. The time constant, τ^*, tells you how long the particles will stay in the box. It has to do with the self precipitation time of the device, with its behavior as a self precipitation device, and with the analog behavior of an ESP with a field generated by the particles themselves. We see that you could calculate the current density, J, to the wall which would be the charge density nq times the mobility, b, times the E field at the wall. But that E field is made by the charge density itself. By Gauss's Law the E field at the wall caused by this charge in the box would just be the charge density, nq, times this distance, L, divided by ε_0. Hence, the current to the wall goes like the square of the charge density, $J = (nqb)(NqL/\varepsilon_0)$. The rate at which the particles NQL inside the box are changing is equal to this current. Typically the rate at which the charge is changing per unit time is some nqL over a time constant. I will call it τ^* because it is going to turn out to be that time constant defined before; $J = nqL/\tau^*$. By equating the two currents, we get $nqb/\varepsilon_0 = 1/\tau^*$, which reduces to the definition of τ^*. So one interpretation of the time constant, τ^*, is as the self precipitation time of particles. If the small particles are replaced by drops, then $\tau^* \to \tau_R$, which therefore has the significance of being the self-precipitation time of the drops.

If you want the simplest model to describe the interaction of charged particles, obviously you just consider two particles. And here I take them with the same radius and consider a simple equation of motion because it will be useful in a moment. We will include inertia. The particles originally have a spacing of s. The equation states that the acceleration is equal to a drag force and a force from the electric field QE. We can consider a collection process that simply does not involve the inertia (we will see in a second that is a good approximation) and consider the time that it takes to bring these two particles together. Now, I am not talking about just one kind of charge particle, but about two kinds. I filled my box with particles so that it is charge neutral. There is no precipitation to the walls at all. There is no net electrical field. The time that it takes the two particles to get together is the same as the self precipitation time. Yet, we have two entirely different problems. Here, there is no net charge. How can the self-precipitation and self-agglomeration times be the same? Well, the particles are spaced only a very small distance apart you see and so this time it takes them to get together can be on the same order as the time that it takes them to get to the walls. Even though the distance is larger for self-precipitation, the E field is spread over space as a macrofield and is larger and more uniform.

You can see that the rate at which we get self-agglomeration is the same as that characterizing a space-charge precipitator. But the end result is far better in the case of the space-charge precipitator because there the particles end up on the walls instead of on each other where they are neutral and not much larger. If you do the same problem of two particles interacting, one small and the other large, and assume as I have that the space between them is very large compared to their size, then you come to what we call cross-agglomeration time τ_d --time for little ones to be collected by big ones. If I had a system of positive drops neutralized by a background of negative particles, this would be the time to collect particles on drops. And finally, of course, if you have a system of collection sites, drops, in a box just like I had before for the particles, the time to go to the wall is this time τ_R and when you put plus and minus drops together in a box so that there is charge neutralizing, at the time τ_R is the time for self-discharge. Self-discharge, not agglomerate--I am going to have to be careful about that word because all we are talking about here is the two drops coming together and neutralizing. Collision doesn't mean they join. That is yet another question. Point number one is that τ^* and τ_R each have these dual meanings.

Now I would like to give you an idea of the kinds of techniques we have been using to control the charging and production of the submicron particulate and the generation of the large drops with which we are working. Then I would like to show you what currently we are doing and what we think ought to be done next. So I am going to ask Ken Sachar to talk about the submicron particulate.

Sachar: To start out with you need a submicron generating facility that can make the aerosols of desired size and desired distribution. Ours was originally conceived by Liu and Whitby (B.Y.H. Liu and K. T. Whitby) based on a collection atomizer which contains a solution of alcohol and DOP. You atomize the solution and make a fairly uniform aerosol. It comes up through a chimney and down through the heating zone which evaporates all the aerosol and leaves you with small impurities where each droplet was.

Then it comes down to a cooling section and recondenses. The oil recondenses on each of these impurity sites and you are left with a very homogeneous aerosol. To make it more homogeneous you sample just from the middle of the tube and because of the cooling effect you have a distribution in size from the outer wall to the inner wall. By varying the concentration of the DOP with respect to the alcohol, you can practically tune your particle size. You start out with a 1.3 micron diameter drop using 100% DOP and you can tune it down to maybe 1 micron if you only use the percent solutions.

Now once you have this aerosol you would like to find out what its size is - there are two ways of doing that. The first where particle radii are greater than 0.2 microns we use an OWL, a device first used I guess by Sinclair and LaMer (D. Sinclair and V. K. LaMer). You are basing your size distribution on the light scattered from these particles. Because the aerosol is fairly homogeneous you can do this sort of thing. If you have a tungsten lamp, you make a parallel beam out of it and focus it through a chamber. What you do is you allow the aerosol to come in and go out through that chamber and fill it. Then along the side is a black window and you orient the OWL vertically and look through the center of the chamber. In most cases the light is between zero and 180 degrees. By going through some calculations and knowing what type of material you are working with, you can find how many times you ought to see different colors. What you will see physically is a spectrum--red, yellow, green, blue, red, yellow, green, blue, etc. The number of times you see the spectrum repeated will be the number of approximately the size of the particles as you can see from a calibration chart. For a 2 micron particle you might see just two reds. As you increase the particle size to maybe 4 or 4.5 microns you will see maybe four reds.

For smaller size particles on the range say from zero to 0.2 microns radius, what you do is rely on the polarization ratio. If you put in a single frequency as from a laser and look at the ratio of the light gathered in the perpendicular direction (polarized perpendicularly or polarized vertically), you will get a curve and the function for that ratio is a function of the particle size. Given the generator, we have been able to get fairly decent results in reproducing these curves in both directions, both for the larger than 0.2 microns with the OWL measurement and the smaller than 0.2 microns with the polarization measurement.

Once you have the particles generated to the size you want you would like to be able to charge them. The next part of that facility is this. We inject the aerosol through this nozzle into the sealed box and we also inject some excess air typically on the order of 25% of the flow. The aerosol that comes out of this nozzle is accelerated into a tube. We can apply voltage between this needle (or the tube) and this metal outlet tubing to get a discharge. That way we can charge the particles. Because they are accelerated toward the outlet flow we don't have nearly as much trouble with losing particles because of the motion of the gas and because of having particles being precipitated themselves on the outlet tube. Once the particles are charged then we inject them into our flow channel. We have two boxes: one charged positively and one charged negatively on a little cart. Both of these feed into a nozzle. By moving the current back and forth we can look at different amounts of residence time while the particles interact for different periods. Typically we are interested in the time on the order of say between a tenth of a second and a second. To see how far the particle interactions have progressed, we use an analyzer consisting of parallel closely packed plates. The spacing of the plates is a millimeter or so. By applying voltage between these plates we can selectively precipitate out particles. If we apply more voltage, the charged particles are precipitated more and more until, at a large enough voltage, we take all of the charged particles out. And if you look at a typical curve you will be able to find and use this information to determine not only the charge but also the mobility of the particles.

One of the tests we have done concerns the self-discharge of particles. Given an aerosol made of half micron particles, we are interested in determining whether they discharge each other in the times of the order of τ^*. As we raise the voltage between the plates of the analyzer, a very small voltage rise gives linear current rises. That is as it should be; using the slope we can find the mobility with which we are dealing. Using these data on initial conditions and using the theory that Dr. Melcher was just talking about we can generate a description of how the particles will behave.

Our experiments would indicate that the particles come together and discharge each other in times on the order of what we expect but we don't have any evidence as yet that discharge implies agglomeration. We can use the polarization ratio of these particles to determine whether or not agglomeration has occurred. Remember that the polarization ratio is a very sharp function of particle size in say the 0.1 to 0.2 micron range so if you made an aerosol originally of 0.1 microns and found that ratio changed drastically to 0.2 microns you would have fairly good evidence that agglomeration has occurred. We will be using this device also as a source of submicron particulate in interaction with water drops and I think Professor Melcher will probably want to talk about that now.

Melcher: You see what Ken has been talking about is getting confidence that this time constant τ^* has the dual significance we have claimed. We have done self-agglomeration and self-precipitation experiments and indeed find the time constant τ^* does govern. There is a lot of background for this end of the scale in recombination theory of ions gases. Much of the theory is the same and many of the quandaries are the same. For our purposes today, we care less that these little particles do or don't agglomerate so the self-discharge and self-precipitation experiments serve to corroborate the significance of τ^*.

Now I am going to talk for a moment about the other end of the particle spectrum--how you make drops and control their charge. This time constant τ_R has meaning once again in two ways. The first droplet generator is a device that disperses the drops in an atomization scheme and I think probably has been tried by quite a number of people. We had this one a number of years ago for a different purpose but found it quite suited to what we are doing here. The atomizer makes anything from 5 to 30 microns. The polydispersity is one of the difficulties. They are generated by injecting air around a capillary needle so that as the drops break away from the conducting capillary change can be induced by a conducting ring insulated from the water by the air stream. You can imagine a fog nozzle similarly producing charged drops. We have tried using two models. This one, which is most generally used, has 20 nozzles and I can give you a rendition of reasons why it is very difficult to use; among them is the fact that it makes polydisperse drops. Also you are very limited by the air injection. Anytime you try to put in any reasonable charge density on the drops it is immediately immensely diluted. Also we have not been all that successful in getting the time constant, either τ_R or τ_d, down to any reasonable value. Typically in a channel into which we inject these drops (one by the way, equipped to study the drop decay by optical extinction and to analyze the drop mobilities) we are injecting so much air that it isn't possible to get more than a time constant τ_d about equal to the residence time. We have worked a lot--I hate to tell you how much with this system--but I am not going to talk much about it today because it does not live up to our requirement for a system in which the electrical, particle, drop and hydrodynamic conditions are well enough controlled to make the results definitive.

Another example of the route you could go is from the 10 micron average size obtained with the pneumatic atomizers to really ponderous drops. Here is literally a barrel filled with water in the bottom of which you have a screen with holes in it. You produce drops which are almost a millimeter in diameter and very densely packed. That's excellent. They are fairly monodispersed and are charged by induction. This is another route to go. You get relatively short times but again they are on the order of the time that it takes for transit through the system and that automatically says you are in a bad way whether you decide to charge half the drops plus and minus so that they don't flow off to the walls or you decide to charge them all to the same sign. You have got a problem here. The drops are so large that the amount of water being used is not realistic. Largely on these grounds we elected not to use this system as the basis for our investigations.

Let us consider next two highly charged streams. By making one inducing electrode plus and one minus, we have plus and minus charges. Thus the drop stream is macroneutral...but highly charged. Or, we can have both drop streams of the same charge. In this case the stream has a net charge.

One immediate index of whether the drops are going to be effective in their own residence time in collecting anything is whether or not they "blow up". If they don't, forget it. The drops are not going to be effective for collecting particulate either. If in fact the drop self-fields represented by this time constant τ_R, aren't effective in the residence time you have got, they aren't going to be effective for collecting particulates that have an even lower mobility than the mobility of the drops themselves. All right, now for the second significance of τ_R as the discharge time--the time that it takes drops to neutralize each other if you decide to make your system charge neutral by putting in as many plus drops as minus ones. You have a stream one half of which is charged plus and one half of which is charged minus. It isn't clear from the photographs whether the drops are agglomerating or not. The point is that the charged drops are deflected but now you have this large neutral beam...a neutral beam that increases as you move the analyzer electrodes down so that in a time τ_R, a time that it takes to go a few centimeters, it is completely discharged. As far as their usefulness as collection sites goes these drops are done. They can no longer collect particulates. So this illustrates the second significance of the time τ_R that I was talking about.

I would like to make one other point. There is a band of particles that have quite a large disparity where they hit the plate and a conclusion from that might be that the particles are not really monodispersed and uniformly charged. But one thing I think very interesting to go through is to calculate the stability of the sheet of charged particles. This is something I have done fairly recently myself for this system. One charged drop will follow another of the same sign only for a distance on the order of a half centimeter. Then the sheet of drops is going to buckle. One drop will go that way and one will go that way and they will spread. Even though the drops are identical in nature the sheet is unstable. I think it is a lesson. We really have to adopt some very different rules for dealing with highly charged particles all interacting collectively from what we would adopt, say, dealing with other slightly charged systems. Most of what is in the literature does not pertain to highly charged systems.

Now what we are doing is interacting these drops with the submicron particulate that Ken was talking about a moment ago. It is sort of an optimization of all the combinations of submicron particulate and drops that we could think of generating to give us a controlled experiment. But the dual significance of τ^* and τ_R, and the fact that τ_d can be on the same order make clear the kind of ambiguity that can easily exist in experimental results unless you are really ingenious in designing an experiment. We hope to have such a controlled experiment by the time this program is completed. By way of illustrating the difficulties, put a box around this system. We inject the drops; then we inject the submicron particulate and we have several possibilities. One--and this is the one that Penney (G. W. Penney) pointed out would be the best back in the '30's but said wouldn't be very practical because it would require too dense a submicron particulate generally--one would be able to make plus drops, let's say, and minus particulate and make $NQ = nq$. In other words, make the system charge neutral. But, you can see now that what happens first is that the beam which is charged to one sign will collect the particulate which is charged to the other sign with what really amounts to a conventional precipitator collection. A charged plate is here equivalent to the drops, the charged particles are out here and the two are coming together. At this stage, it is not a particle collecting on a drop at all. It is at first a bunch of particles collecting on a sheet of drops. Finally, when the particulate gets into the drop beam, it is going to be collected in a particle-drop sense and my point is that the same time constant τ_d governs both of these processes. More than that, if we were to make a box and inject into it the particles and leave the beam out altogether, the collection rate would have to be about the same. This, I think, is essential to placing the charged-drop scrubber in perspective relative to the ESP. Just charge the submicron particulate, shoot it into the box and what you get out is going to be as clean as it would be if you put the drops in. What is the difference between the two cases? It is the difference between where the particles end up. They are either going to end up on the walls or they are going to end up on the drops. If what we have is a scrubber and you would like to make it collect particulate below

10 micron much more efficiently than it will otherwise and your scrubber is probably already serving another function, then charging the drops and the particles is a good way to go. The electric field makes sense. But if your competition is another electrostatic precipitator, a conventional one, then you have got some other criteria to meet and I would just like to talk about that and one other thing before I quit.

Now as I say, don't misunderstand me. I think that using electric fields to augment scrubbers makes a lot of sense but I think we have to have it in perspective. There is not going to be any breakthrough in terms of getting much shorter times--there cannot be--and we have no evidence yet that there is. But it can be a new mode of approaching particle control problems in the context of handling other problems such as the control of gases.

Finally, consider now how the use of particles as collection sites and electrically induced agglomeration can more than compete with the ESP. The idea is that you use as collection sites particles suspended in a fluidized bed. You say, well, that is no way to use a bunch of drops. I am not talking about drops. I am talking about particles probably made up of the same material as what you are trying to collect. Let's say we are trying to collect coal ash made up of coal ash particles themselves. I will try to draw a system here so that you can see how it is scaled. But if you can take any micropart of this the particle surfaces function as a pair of electrodes. Of course, a critical part of the system is the distributor plate here at the bottom which hopefully doesn't have too large a pressure drop. We have the large particles, which typically for a 1 foot per second*throughput would be in the area of 60 microns in diameter, in a fluidized state. Here they are, bubbling away, with the dirty gas coming through and then, hopefully, the clean gas coming out. Now what we do know about these beds is this. That if you apply an electric field to a fluidized bed and especially if they're insulating particles, the effective size of the particles is made much greater. You could have a bed (and we have done some experiments) like this shooting up into a cone placed over it - elutriation very very high and turn the field on and it will collapse into a well organized bed. By varying the electric field you can take a fluidized bed (and that is why we call it an electrofluidized bed because it is an entirely different beast) all the way from an ordinary bubbling bed, as I just described, to a frozen state or an absolutely fixed bed. There it is, fibers of material in the bed. By turning off the voltage you release the whole thing. The collection time of such a device is astronomically better than even the ESP and that is why I think its development is worth a gamble.

Discussion: The floor will be open. Let's keep the questions to five minutes. Do I have some questions?

Drehmel: Dr. Melcher, the fluidized-bed concept is very interesting, maybe new. One question comes to mind is how do you keep the fluidized particles in a charged state? You need to keep them in a charged state.

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*EPA practice is to use metric units for quantitative descriptions; however, units were left as used in the original presentations. Readers more accustomed to metric units may use the conversion factors tabulated at the end of this document.

Melcher: Yes, you bet. And I really appreciate the question. The whole point of this business was that when you got the large NQ's it was going to discharge very quickly and if you want the ability to collect in a very short time it is synonymous that they go into discharge in a very short time and I think that is a fair statement that if you have particles that closely packed then they are going to discharge each other almost instantaneously and as I say that needs clarification. There are really two limiting cases that I think we want to think of. One of these pertains to, let's say, the collection of oil ash. We are doing experiments with Con Ed in which we are trying to fluidize of all things oil ash particles and we have made fluidized-bed experiments in which we have put a voltage across particles. Now how do particles in a state such as this remain charged or very clear if you do an experiment with macro particles? The particles in there are busy doing this. They are all the time in a highly kinetic state and the rate at which they bounce against each other is determined by the electric field. I think all of us have probably seen experiments in which you put a particle next to a wall usually the electrodes are this way and the voltage across it and you get particles bouncing back and forth. The particles, let's say we have a plus voltage like that, acquire a minus charge and take off for the upper electrode. The minute it hits it, it recharges and goes back. Now if you have at any instant this box with charged particles, that is a mechanism we have done quite a bit of work on, but the point is that they are so densely packed in the fluidized bed that they make an excursion only a short distance, they strike another particle and exchange charge with it which will be evidenced thus far and then they start back again. They have reversed their polarity and back they go. But at any instant they are highly charged. Now how do you pay for it?... with the current. The thing will draw quite a bit of current. The current is an extremely critical factor. As a matter of fact the current and hence the loss in a bed of graphite particles goes up with a fantastic power law. Nevertheless, we have been able to show you could get enough field in the bed that it could be effective. Now let me go to the opposite extreme. Supposing the particles are so insulating that you don't put any charge on them at all...then they are so densely packed you get the polarization interaction. The fact is you don't need any charge on them. Between one particle and another, you see, will be E lines which just due to the dielectric constant, tend to come into the particle. The particle now has no net charge. There is as much positive polarization charge on one end as negative on the other. So the particle never has net charge, yet it is a very good collector. Because of the closeness of the particles and particulate it can be far better than the ESP. So that at the opposite conductivity extreme I would say don't charge the particles at all...just polarize them. Probably the truth in any practical application is somewhere in between.

: How did you get rid of the charge of the particles you collected transferred to those highly dielectric particles?

Melcher: If they were highly insulating? I think in that case you would probably bi-charge the gas entrained fine particles entering the bed. It is a very good question. There is no reason why, if you are trying to collect small particles on dielectric particles (which generally I don't think we would) inject charge neutral, plus and minus. In the coal ash area a likely candidate is highly insulating coal ash. By the way, the charge is not altogether necessary. Insulating particles polarize and they collect together in that state. You would have to see the bed to really appreciate that state of agglomeration we are talking about. It is comprised of "strings", and these can happen purely by polarization. You don't have to charge the particles at all and that is true at what has been collected as well as what is to be collected.

: So the particle you are collecting is the same size roughly as the ones comprising the bed?

Melcher: The collection sites have to be effectively over 40 micron size or they are not going to stay in the bed. With the field applied these particles are agglomerates and certainly bigger than the one you are trying to collect. But the sites and pollutant are the same constituents and if there were no adhesion on your side (and that is why it is extremely important that experiments be run at temperature) the particle removal is a very hard thing to imagine. We are trying to apply the EFB concept to oil ash.

Presentation No. 2

APPLICATION OF CHARGED DROPLET SCRUBBING TO FINE PARTICLE CONTROL

by

Mr. C. Lear
TRW Systems Group

Drehmel: I would like to introduce Mr. Charles Lear at this time. Mr. Lear is a research engineer in the Environmental Control Technology Section at TRW Systems at Redondo Beach, California. He is currently active in programs for measurement and control of dust and gas pollutants. He is a program manager of TRW's EPA Contract to study application of charged droplet scrubbing to fine particulate control. Chuck has been with TRW for 12 years, and has played an important part in the early beginnings of his own charged droplet scrubbing concept which is now 4 years old. He holds an MS in Mechanical Engineering and an MS in Physics both from the University of California.

Lear: I will begin my comments by noting that the TRW charged droplet scrubbing concept had its genesis in space technology spinoff. We had an Air Force funded program to develop a small thrust space engine (colloid thruster) which operated by an electrostatic spraying process. It operated in a vacuum and put out thrust on the order of micropounds. A thrust of one millipound is obtainable by combining several modules. People at TRW realized we had to diversify out of the space industry. Electrostatic spraying is a standard process and we had a good technology base for it through the colloid thruster. The question arose, "What else can we do with it to broaden our use of it?" The result was the idea of using a charged droplet spray in an air environment, a dirty air environment, in order to clean the air. We tried it and it worked. We later learned that it was not an entirely new concept, that other people had been there before us. But we did have some novel features that made it worthwhile pursuing. So we did and we went through programs of company sponsored independent research followed by programs to commercialize the device. All this is still going on. Now we are in the fortunate position of having government funding to support investigation into basic scrubbing mechanisms.

I shall first summarize the program which is called, "The Application of Charged Droplet Scrubbing to Fine Particle Control." There are four tasks or phases: task analysis and evaluation; an experimental research phase in which we are actually going to study basic mechanisms and look carefully at the interaction of droplets and particles on an experimental basis; then we will build up a unit, a selected unit using selective mechanisms, to actually test efficiency; and finally we are going to try and project into the future and see what we can do on a pilot scale. The emphasis on this program is twofold. One is that we are going to investigate the performance of a charged droplet scrubber with what you might call submillimeter particulate; that means 10 micron range,and perhaps 1 micron and submicron ranges. The submicron range is of course what we are really interested in ultimately. Also, we would like to draw performance comparisons of this device with the performance of electrostatic precipitators and other conventional equipment. I should say that the program is newly started and what I have to present here is not really coming as much from EPA funded work as from what we have done before this.

Our takeoff point for analysis and classification is work that was published in August of 1971 by Jim Melcher. Figure one shows the Melcher

Figure 1

Modified Melcher Classification of Droplet-Particle Interactions

Class	Drops Charged	Particles Charged	Ambient Electric Field	Terminology
I	No	No	None	Mechanical Scrubbers
II-A -B	Yes	No	Imposed Space-Charge	Electrical Scrubbers
III	Yes	Yes	None	Electrical Agglomerators
IV-A -B	No	Yes	Imposed Space-Charge	" "
V-A -B	Yes	Yes	Imposed Space-Charge	Hybrid Electrical Scrubbers

classification of droplet-particle interactions. This table does not explain or describe the actual mechanisms, but rather classifies devices. It is drawn up to present a phenomenological picture of the interactions. The scrubbing devices are broken up into 5 classes and the columns of the table indicate this. Conditions are shown within the scrubbing device as to whether or not the droplets are charged, whether or not the particulate is charged, if there is an ambient electric field, and what is its nature--it can be either externally applied or it can be induced or imposed by the space charge within the particulate itself. Finally, there is a terminology shown in the table which is growing up around this classification and it partially existed before it. Class I is a conventional mechanical scrubber, for example. Class II type devices we generally call electrical scrubbers. Classes III and IV are electrical agglomerators. I think this is what Dr. Melcher has described today in his programs. And Class V may be thought of as a combination of Classes II and IV really. It is a hybrid device. This table has been modified a little bit to show the difference between the space charged induced electric field and the applied fields.

Figure 2 shows the new force mechanism classification which we are working on and which we intend to work from. This gives more of an emphasis on interactions as opposed to a phenomenological classification. These types of mechanisms are seen within the various Melcher classifications and each of the Melcher classes is assigned generally one dominant mechanism from here. For example, in the mechanical scrubbing device the most dominant mechanism is the mechanically induced relative velocity resulting in direct impact between droplet and particle.

Figure 2

PARTICLE REMOVAL MECHANISMS

A FORCE DESCRIPTION

A. Droplet-Particle Interaction Mechanisms

- 1.0 Direct Collision and Agglomeration
  - 1.1 Inertial Impact
    - 1.1.1 Mechanically induced relative velocity
    - 1.1.2 Electrically induced relative velocity
  - 1.2 Electrostatic Attraction
    - 1.2.1 Monopole Forces
    - 1.2.2 Dipole Forces
  - 1.3 Wake Entrainment
  - 1.4 Molecular and Turbulent Diffusion
- 2.0 Induced Charging
- 3.0 Droplet-Evaporation Charging
- 4.0 Condensation Particle Growth

B. Corona Charging

Going down the list, the direct collision and agglomeration mechanism can come about in two ways:either mechanically inducing a relative velocity, as I have already suggested; or by applying an electric field and thus obtaining an electrically induced relative velocity. If you have separately charged particulate and/or droplets you can have electrostatic attraction forces. I have classified these also. This classification needs a little clarification here. What I mean by monopole forces is the force between two monopoles generally oppositely charged. Dipole forces are the forces that occur on a droplet in which there is dipole induced by an applied field. This is a strong interaction mechanism. The field lines tend to enhance the collection cross-section by a factor of three. However, the droplet is not interacting with another dipole, but with a particulate monopole. It is a dipole-monopole interaction and the particle that we are collecting is probably going to be charged. If it is not then you get a dipole-dipole effect and this is very weak.

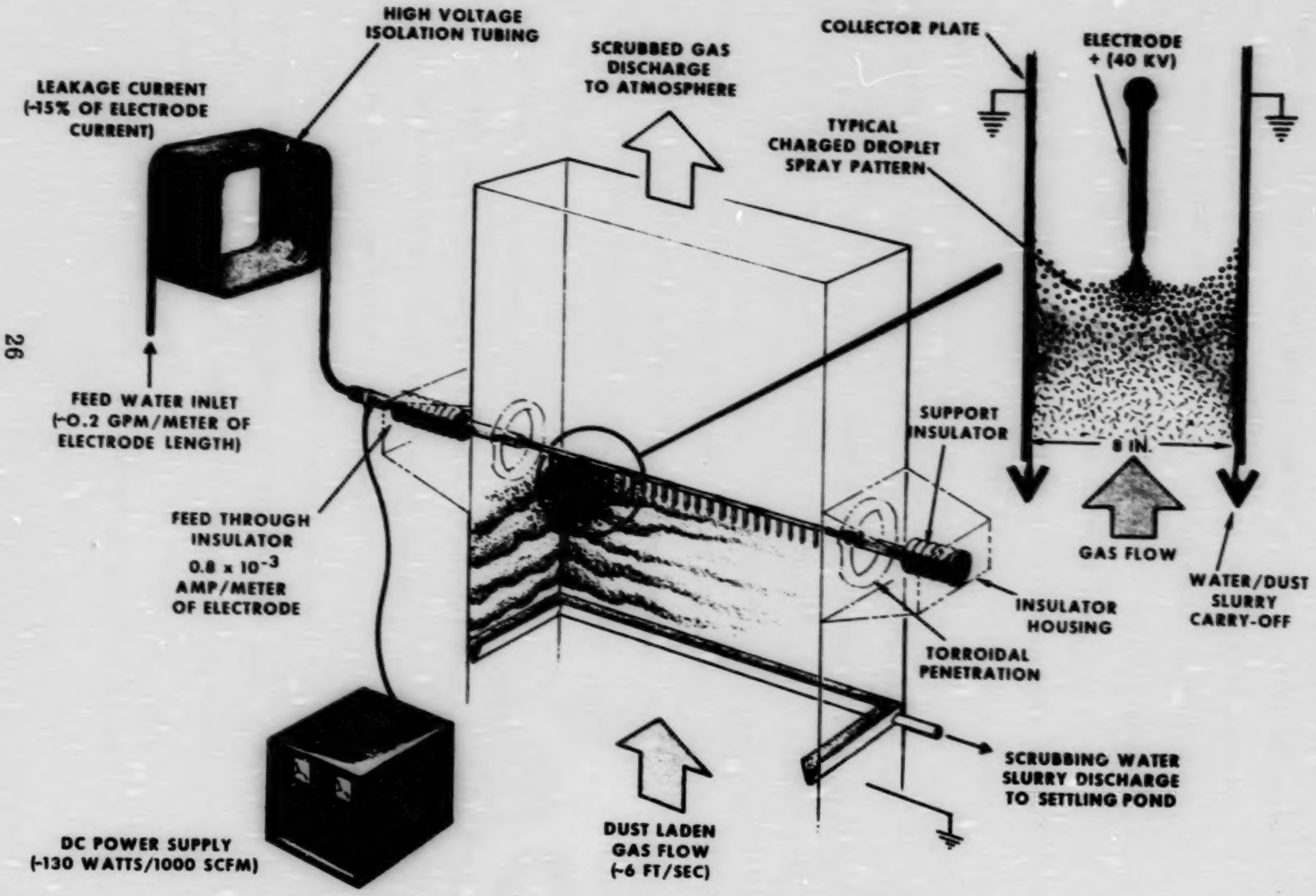
Induced charging, also shown in Figure 2, is a phenomenon that deserves special attention. It is peculiar to electrical scrubbers and not too well discussed in the literature. Induced charging occurs when a very small particle approaches a large, fully-charged droplet. It tends to miss the droplet because it doesn't have inertia enough to carry it across flow stream lines to collide with the droplet. Often it will get close enough so that it can produce a strong enough electric field between droplet and particle to cause a discharge. Thus a neutral particle can thus obtain a positive charge without actually colliding. The droplets are charged positively. The result is perhaps that the particle will be repelled from the droplet but it does retain charge and then it can be precipitated.

Droplet evaporation-charging is a mechanism at which we are looking more carefully. This is our own coined phrase. We ask what happens if a droplet is traveling through a dusty gas and the vapor pressure of the droplet medium in the gas is low; low enough so that the droplet might evaporate. As the droplet becomes reduced in size the electrostatic forces around it are going to reach breakdown limits. The droplet will tend to become unstable and break up into smaller droplets or molecular clusters. This process occurs until eventually you are left with droplets small enough that they are only clusters of charged atoms and molecules. There is charge dispersed by this mechanism. It is not a true corona discharge, but it comes about by a charged molecule leaving the surface of the droplet, and "evaporating", if you will. This is a process that we are going to study a little bit more deeply.

On each of these classifications or mechanisms our objective is to obtain pertinent time constants. Each of these mechanisms will have a characteristic interaction time. It is convenient to try and classify the mechanisms all on a common basis, and a time constant is a good way to try and do it.

Figure 3 shows the TRW Systems charged droplet scrubbing concept. There is a hollow electrode through which is passing the scrubbing liquor--generally water--which comes out through a series of spray tubes and enters the dusty gas which is flowing upwards against the spray. The water is drawn off of the tips of the spray tubes by means of electrostatic forces. The water flow rate is such that the water reaches the tip of the spray tube just as fast as the electrostatic forces can pull it off with a maximum charge on the droplet. The result is electrohydrodynamic spraying. The droplets are then drawn rapidly towards the walls by electric field forces.

Figure 3. TRW SYSTEMS CHARGED DROPLET SCRUBBER OPERATING PRINCIPAL


HIGH VOLTAGE ISOLATION TUBING
LEAKAGE CURRENT (~15% OF ELECTRODE CURRENT)
SCRUBBED GAS DISCHARGE TO ATMOSPHERE
COLLECTOR PLATE
ELECTRODE + (40 KV)
TYPICAL CHARGED DROPLET SPRAY PATTERN
FEED WATER INLET (~0.2 GPM/METER OF ELECTRODE LENGTH)
SUPPORT INSULATOR
8 IN.
FEED THROUGH INSULATOR
0.8 x 10^-3 AMP/METER OF ELECTRODE
GAS FLOW
INSULATOR HOUSING
WATER/DUST SLURRY CARRY-OFF
TORROIDAL PENETRATION
SCRUBBING WATER SLURRY DISCHARGE TO SETTLING POND
DC POWER SUPPLY (~130 WATTS/1000 SCFM)
DUST LADEN GAS FLOW (~6 FT/SEC)

They have an electrically induced velocity relative to the gas stream. The scrubbing efficiency is favorably affected by the high velocities thus obtained.

Figure 4 shows a schematic representation of collision effectiveness probability. This is simply the probability that a droplet and a particle on a geometric collision course will actually interact, either by impaction or by induced charging. It is the same as droplet collection efficiency. In Figure 4 are the droplet radius S, the particle radius Rp, and the distance of closest approach, D. The vertical position circle shows a locus of the direct approach path of the particle for grazing impact. The particle will follow flow stream lines, which tend to go around the droplet. If induced charging occurs, a "grazing" impact is one which brings the particle close enough to the droplet for charge exchange to occur. The plots shown in Figure 5 were made using an analytical model derived by Irving Langmuir, which assumes a Stokes flow field around the droplet. The collision effectiveness probability will always be less than one. The computations show that the collision effectiveness probability is 1 for the larger particulate and tends to fall off rather drastically as the particle size drops down. The total collision probability shown here refers to the combined effects of direct impact and induced charging. If the particle is more irregularly shaped it will discharge more easily in a lower field.

Mass removal efficiency can be derived, and its derivation leads to the set of equations shown in Figure 6. Eta is a mass removal efficiency. There is an integration over the particulate mass distribution, M. The fractional removal efficiency is an exponential. Under the exponent we have a parameter called Γ_a which is the droplet flux in droplets per square

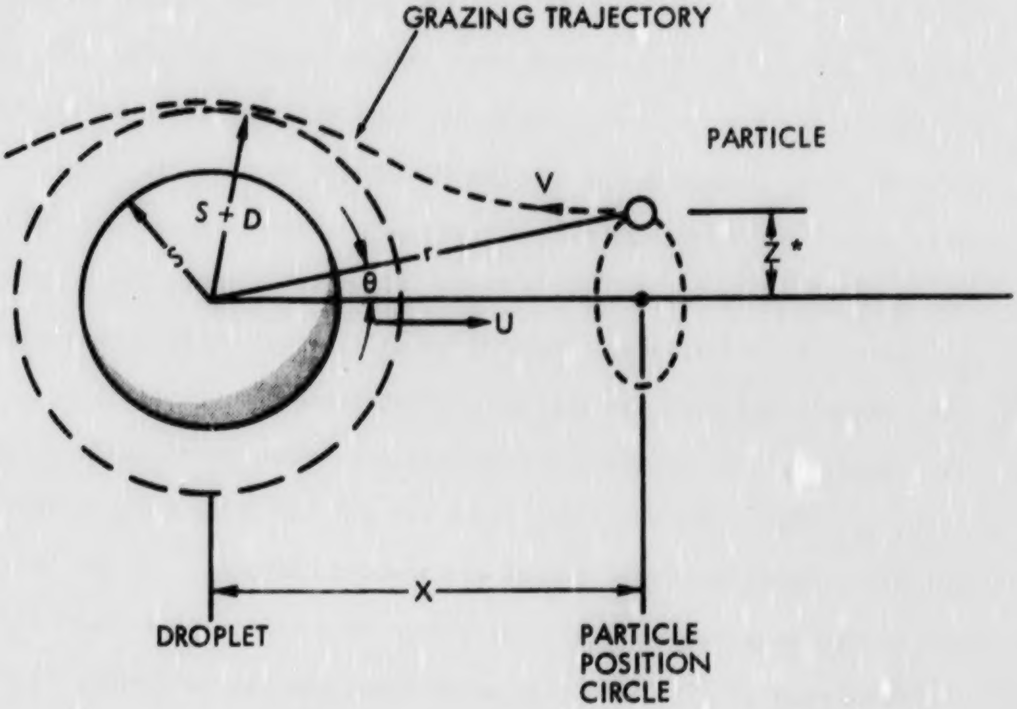
Figure 4

DROPLET-PARTICLE INTERACTION MODEL

$P(r_p)$ = collision effectiveness probability

= probability that a droplet and particle on a geometric collision course will interact

r_p = particle radius



GRAZING TRAJECTORY
PARTICLE
V
S + D
S
r
θ
U
Z*
X
DROPLET
PARTICLE POSITION CIRCLE

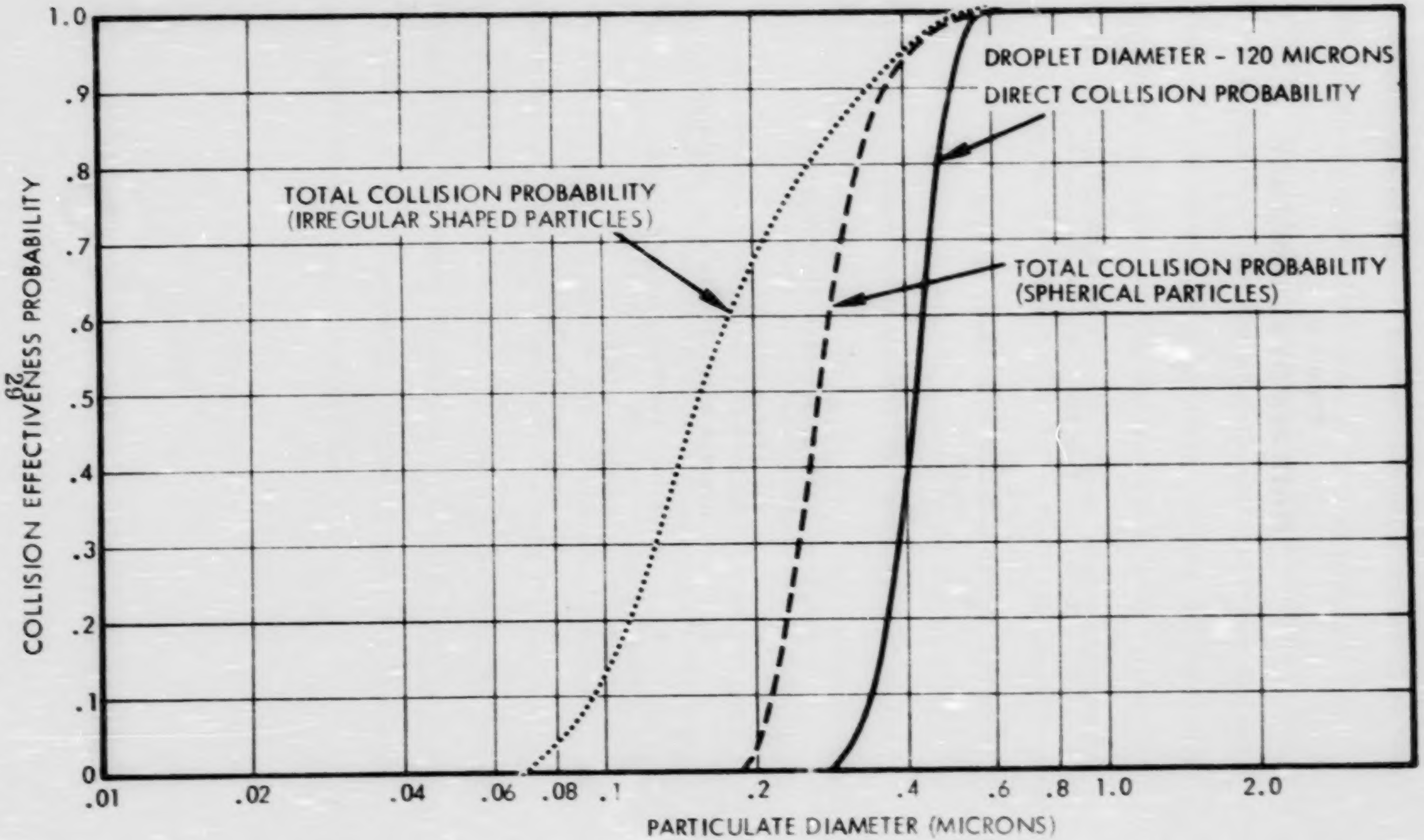


Figure 5. Collision Effectiveness Probability - 120 Micron Droplets

Figure 6
MASS REMOVAL EFFICIENCY

$$\eta = 1 - \int dr_p M(r_p) \exp\left[\frac{-\Gamma_a \pi S^2 P(r_p) L}{W}\right]$$

$$\Gamma_a = \frac{\alpha \epsilon_0 \bar{E}_c E_a}{3\pi\mu\ell S} = \text{droplet flux}$$

α = mass utilization efficiency

$M(r_p)$ = particulate mass distribution

W = gas stream velocity

$\bar{E}_c$ = average electric field at collector

E_a = volume average electric field

ℓ = scrubber width

L = spray pattern length

centimeter per second. The droplet flux has a factor alpha in it which is related to the efficiency of droplet charging. An important effect is corona charging from the electrodes. This must not become dominant, and the droplets must not become too small because then the current is space-charge limited and this has an effect on the efficiency. The droplet flux is proportional to $1/S$ and not $1/S^3$ because we are not talking about constant water flow rates but we are tailoring the water flow rate for an optimum scrubbing efficiency to get the maximum field on the droplets. The maximum field on the droplets is assumed to be the breakdown strength of the gas through which it is moving, corrected for droplet radius of curvature. So by looking at this equation we have an S squared in the numerator of the exponent and we have r_a, which is proportional $1/S$. The total exponent then is proportional to S and the result is that the efficiency increases with increasing particle size. This is a good reason for making our droplets large: so we tend to run at an optimum droplet diameter somewhere around 100 microns. If you get the droplets too large for the applied electric field, you wouldn't get the optimum charge on the droplets. In other words, the charge on the droplet and the field surrounding the droplet will be less than it could be if the field were equal to the breakdown strength of the gas medium.

Figure 7 shows theoretical efficiencies for the CDS, calculated for 2, 3 and 4 stages, for an 8-micron geometric mean diameter particulate. Performance is functionally dependent on gas stream velocity. Pre-program models for collision effectiveness probabilities were used in this calculation. Field test data obtained in Chucoku, Japan show substantial agreement with the predictions.

Figure 8 shows results of a CDS pilot installation field test conducted at S. D. Warren Company, Muskegon, Michigan. The CDS was installed as a secondary unit at the outlet of an electrostatic precipitator controlling emissions from a kraft process recovery boiler. The fume at the CDS inlet was, on the average, 15 percent by weight under 3 microns in diameter. The resulting geometric mean size of the number density distribution is about 1.5 microns.

The table shows inlet grain loadings and cleaning efficiencies in two classifications, particle size greater than and less than 3 microns. Results are shown for two and three stage operation. Efficiencies were obtained by inlet and outlet sampling. The larger particle distribution was sampled with a Brinks cyclone. The sub-3-micron range was sampled with a Brinks mist sampler, Model "B" impactor, followed by a glass pack and impinger. The impinger catch, which was included in the efficiency calculation, was later found to have precipitated small amounts of colloidal sulfur from the H_2S contained in the flue gas. The precipitate was formed in the impinger water.

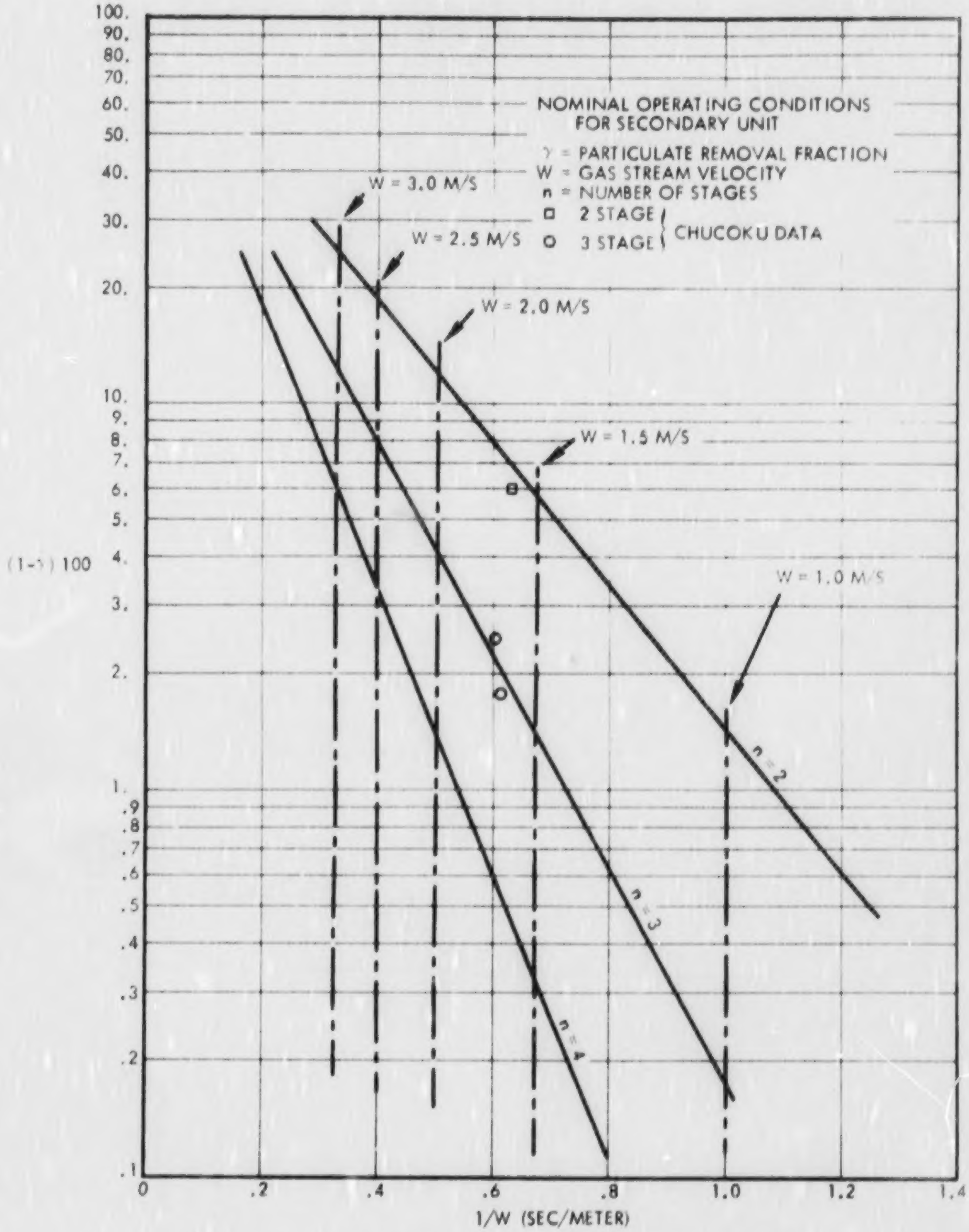


Figure 7. Theoretical CDS Efficiency for 8-Micron Geometric Mean Diameter Particulate

Figure 8. Performance Summary: S. D. Warren Co. Kraft Process Recovery Boiler, CDS Pilot Installation

	Inlet Loading (gr/SCF)			Cleaning Efficiency (Weight %)		
	Total	>3μ	<3μ	Total	>3μ	<3μ
Three Stages	0.0848	0.0631	0.0217	89.9	91.4	85.3
	0.1119	0.0784	0.0335	85.4	95.4	61.8
	0.2156	0.1627	0.0529	85.4	96.2	60.0
	0.7446	0.6302	0.1144	94.9	98.3	76.0
	2.328	0.213	2.115	84.7	78.4	85.4
Two Stages	0.2156	0.1627	0.0529	80.5	93.7	39.7
	0.3297	0.2680	0.0617	88.2	96.5	52.0

Questions:

: Your graph of the collection efficiency as a function of particulate size showed awfully high collection efficiencies compared with what we normally see in the literature. Do you have any explanation for this? You were showing a collection efficiency approaching 1 with the particle size of about 0.8 micron and I guess I had never seen one that high.

Lear: The collision effectiveness probability is quite high and I don't know that I can comment on comparisons with what is seen from the literature because I haven't seen that much of what has already been published. I know that as the particulate size gets large you rapidly approach a state where the particulates have no problem in crossing the stream lines which they must do in order to impact the particle.

: No charge on that?

Lear: Yes, there is. Yes, the droplets are charged but not the particulate.

: Do you have a parameter here or have you stipulated what the charge on the particle was?

Lear: The particles have no charge. The droplets are maximum charged in the sense that they break down the field; that is, the field strength of the surface of the droplet is a breakdown field.

: That is no different from the reaction parameter or any other removal mechanism relationship for particle size. You can move that thing any way you want depending on what you do with the parameter but that doesn't mean that a device built using that mechanism is going to operate anywhere near our 100% percent. It is all a probability. That is all that is.

Lear: This is like a cross-section. That is all it is. Of course in computing the efficiency you have to take the droplet flux parameters and gas velocity...

: You take the configuration you are going to use.

As edited into the test for publication, the Langmuir model (collected works of L. Langmuir, C. Guy Suits Ed.) was used for the direct impact portions of the collection efficiency calculations. This model, based on a Stokes flow assumption, is theoretical and analytical. It has since been found to be in disagreement, on the high side, with theoretical solutions of the complete Stokes flow equations of motion. The disagreements are not striking, but they are on the high side. I do not now believe the disagreements with measured data to be very serious either.

An important parameter in Figure 5 is droplet charge, which by virtue of the ambient electric field results in droplet velocity relative to the scrubbing volume. The assumptions made in preparing Figure 5 lead to a droplet velocity of nearly 300 meters/sec. with Stokes flow. In fact, the droplets are too large and fast for Stokes flow assumptions to be valid, and the velocity is actually about 30 meters/sec. In either case, the higher velocity will result in a larger collision effectiveness probability.

: Do you bring a single data droplet to compare with this? This is a single droplet calculation. Do you have any experimental data perhaps to compare with these calculations?

Lear: No. This is one of the purposes of the present program to get into this and actually see how close we can get this to really measured collision effectiveness probability.

Hendricks: There is some data on single droplet collision. We did some charts on both charged and uncharged droplets, calculations and experimental data. There is a great body of literature,I presume everyone in here is familiar with,in the atmospheric physics area and this problem has been approached for many many years for the collision and coalescence of water drops, the situation where you have external fields, where you have no external fields, where you have the drops charged/uncharged. The whole problem has been studied for a long time from the different point of view of throwing raindrops on saturated atmosphere without the electric field finding that it just can't rain in North Carolina.

Lear: We appreciate the reference.

: I would add one point to that remark: and that is an extremely dilute environment compared to what we have got. We did that and that is the selective part of this whole....

: Particle interaction?

: Yes, but once you submit the collection all interacting at once which is the essence of the project.

Lear: We had not been aware of even the single droplet experiment. There is some work we found I think on the 10 micron droplet collecting with the water vapor maybe 50 micron droplet but on the smaller capability we are not aware.

Sparks: A good reference for that would be B. J. Mason's Physics of Clouds in the second edition which is about 2 years old. It does in fact have all these calculations in the appendix.

Lear: Could I make one more comment and then cut it?

Hendricks: I would like to make one comment that the problem that people seem to be ignoring -- maybe it deserves to be ignored -- that's the problem of charged maintenance of large drops in a high temperature environment which is by no means trivial. If the drops are that great they don't evaporate a charge. The contention is that they evaporate neutral and you do reach the limit in many cases quite soon. But it turns out that these drops are not shown to break up into two equal size drops which remain charged. The probability is much more, much higher that the drops will remain the same size and spew off very very tiny drops and almost totally discharge the larger drops. That is probably one of the main mechanisms. There is another mechanism that operates to discharge the drops that occurs depending on the size of the drops almost as soon as the rating of it does and that is electron avalanching into the particle or away from the particle almost a local gas breakdown phenomenon that just totally discharges the particles and ends up with charged drops. I think this is for drops which are volatile, which have high vapor pressure and high temperature environment. This may be a very serious problem in an actual device.

: It shows up more as just a single or low multiple electron avalanche to the surface of the particle and the avalanche almost totally discharges the particles and if the particles are charged negatively then it will avalanche away. But it is a discharge mechanism that is not associated with any mass loss of the particle but the particle is almost totally discharged very quickly. The fields at the outside of the particle don't have to get up to breakdown strength of air for this to happen.

Lear: Thanks, I will follow that.

Presentation No. 3

WET ELECTROSTATIC COLLECTION OF FINE PARTICLES

by

Dr. M. Pilat
The University of Washington

Drehmel: Dr. Pilat is Associate Professor of Air Resources Engineering, Department of Civil Engineering, University of Washington. Mike teaches engineering courses, design of air pollution control equipment and source testing. His research interests include design and evaluation of particulate, air pollution control equipment and plume opacity. He holds a B.S. and M.S. in Chemical Engineering and a Ph.D. in Air Resources. His Ph.D. was on light extinction theory applied to absorption of gaseous pollutants onto aerosol particulates.

Pilat: Thank you. Similar to that by Lear on the collection efficiency function of particle size, this curve shows the traditional dip right there between a tenth of a micron and about 2 microns radius which is a classic problem for fine particulate matter. Now this is a curve based on the part of the equation of motion. That was a single droplet collection efficiency. This is the overall collection efficiency for cyclonic wet scrubber and it also dropped right off at the 1 micron region and I think this is fairly widely accepted. As far as the scrubbers go, that is a good part of the problem right there is collection below say 0.5 micron.

I noticed on the agenda it says Wet Electrostatic Particle Collection and I think perhaps it should be better titled let's say, "Droplet Collection of Fine Particles" because I will mainly speak with regard to droplet scrubbing.

O.K. Next the calculations of the fractional collection efficiency of a single droplet and the function of the particle radius comparison between the noncharged case and the charged droplet charged aerosol particle. The single droplet collection efficiency stays up to a fairly reasonable magnitude through the region based on these calculations and reports by Cramer and Johnstone and Penney's (G.W. Penney) classic patent of 1944-45 We constructed a single chamber 140 CFM scrubber, with a mid-fire chamber used to bring the humidity up to 100% in order to eliminate possible diffusiophoresis effects. A di-butyl phthalate aerosol was generated by injecting the DBP into an electrically heated aluminum tube, 1.5 inches in diameter and 18 inches in length. The DBP condensation aerosol passed through a blower, a corona charging section, and into the scrubber chamber. The scrubber chamber and ducts were constructed of 1/4 inch thick Lucite. The corona charging section consisted of a single 12 gauge steel rod mounted horizontally in the middle of the rectangular inlet ducts with ground strips of copper and was charged to 27,000 volts. The chamber (45 inches high and 20 inches in diameter, cylindrical) was co-current and had a water flow of 1.0 gallons/minute with 13 spray nozzles. The spray nozzles were Spraying Systems Fogjet 7N4 nozzle tips. The water droplets were inductively charged positively with a 5 kilovolt power supply. The particle mass concentration and size distribution were simultaneously measured at the inlet (upstream of the charging section on the first chamber) and outlet of the electrostatic scrubber using Mark III University of Washington Sources Test Cascade Impactor. These cascade impactors are similar to those reported by Pilat, Ensor, and Bosch (1970) and are commercially available under a licensing agreement with the University of Washington. The DBP aerosol mass concentration at the inlet to the electrostatic scrubber was typically about 0.15 grains/acf.

The size distribution of the water droplets was measured by collecting the droplets on greased (melted petroleum jelly) glass slides and photographing them as described by Pigford and Pyle (1951). The droplet images on the photomicrographs were sized with a Zeiss particle size analyzer. As the water droplets from hemispheres on the greased slides, a conversion factor of 1.26 was used to correct the flattened diameter to the real droplet diameter. About 700 droplets were sized for each distribution measured.

The electrostatic charges of the aerosol particles and the water droplets were measured with a similar device which basically consisted of a sample collection section and a charge measuring circuit. The aerosol charge analyzer involved a 1 inch diameter Gelman filter holder with a Type A glass fiber filter to collect the particles. The filter holder and nozzle (for isokinetic sampling) was electrically insulated from a grounded aluminum shield which protected the filter holder from external electric fields. The electrostatic charge measuring circuit included a 1000 picofarad capacitor and an operational amplifier circuit. The aerosol charge to mass ratio was obtained by monitoring the current for a recorded particle sampling time and then weighing the filtered particles. The aerosol charge was typically about 5.3×10^{-5} Coulombs/gram (3.6×10^{14} electron units/gram) in the first scrubber chamber.

The droplet charge analyzer included a 3 inch square droplet collector (packed with aluminum shavings) connected to a grounded microammeter (10^{-7} to 10^{-8} amps). The droplet charge analysis consisted of placing the collector in the spray droplets, monitoring the current and sampling time, and weighing the amount of water collected. The droplet charge with 5,000 volts inductance charge was typically 5.6×10^{-7} Coulombs/gram (3.8×10^{12} electron units/gram).

O.K. Getting down to the nitty gritty part, the collection efficiency has a function of the particle diameter. The overall particle collection efficiency for this particular setup was on the order of 35% with no charging and say 60% with charged droplets. In other words, opposite polarity charging. And the intermediate cases of charged aerosol probably will be appropriately in the middle. For our particular case here it doesn't seem to make much improvement compared to the uncharged situation. Now you will notice something strange I think and that is the negative collection efficiency business and we were not too happy about that for a couple of reasons it possibly might have occurred. Not drying the filters on the outlet side being as it was a scrubber and some other things but we never resolved it and we have never seen it since. So hopefully that was an anomaly in the measurement and will show much more curves than what occurs later but where we don't see this.

O.K. Based on these results we changed the system. Actually made our humidifier into another charged chamber so that the first chamber is countercurrent and the second chamber is cocurrent and also changed to a

DOP rather than DBP aerosol. Ran it in this mode measuring the collection efficiency at the, I mean, excuse me, the size distribution simultaneously at the inlet and outlet to get the collection efficiency charging the water positive and the aerosol particles negative. And based on these tests we got down to 0.3 micron roughly; it collected about 30% on the uncharged case and about 85% for the charged case increasing the efficiency at the higher larger size. Using a fairly large amount of water, 15.7 gallons per thousand cubic feet, the overall efficiency is going from 50% to 69% uncharged to about 95 to 98% overall under the charged mode which we thought was quite nice.

We did not vary the concentrations to a great degree. In that concentration is about 0.2 gram per standard dry cubic foot and these are run at room temperature. It was not of course in the field. It was in the lab test and our concentration runs on the order of a hundredth of a grain.

O.K. Now based on this we designed and constructed essentially an 800 to 1000 CFM unit, a larger unit, filter chamber, built it all out of Plexiglas so that we would see what was going on inside. University of Washington cascade impactors were used for simultaneous inlet and outlet particle size determinations.

We are using a bar filter to clean the gases that go outside the building. We are right near where they are building a new Husky Union building and they do not look favorably upon our emissions. Unfortunately it goes right through it and there is a blue haze out there when it is not in the operating mode, I mean the charging mode. We will have to do something about that. They have designed a stack to take care of it.

We have a lot of problems with the stray field fouling up our current measurements on the charged mass aerosol and droplet. A lot of things shield and reduce this problem. We haven't completely solved that. Our droplet charging is just a funnel which runs out and it goes through the electrometer and we have tried to mark here on all the tests, the charging mass and the droplet and the aerosol so we could find out what sort of a charging substance we have. And of course this view just shows our power supplies and up here we have, it is set up with eight banks spray nozzles per scrubber so we can grade the liquid to gas ratio and relationship between the collection efficiency and the spray system.

O. K. Take a look at the results. They are rather fresh, August 30th. Put the drops and particles oppositely charged. We are getting up on the 90% collection efficiency for the 0.4, 0.3 micron diameter particles whereas for no charging it is quite low. This was a 700 CFM operation. Overall collection efficiency was some 91% with charging about 47% no charging and we were quite happy about that liquid to gas flow rate ratio being in the 1 to 2 gallons per thousand cubic feet range. That is what I think was one of the greater problems. Our former system was getting us in the high water usage. Our greatest energy utilization is in the pressure for the water spray running around 100 psig on it. When we up the water flow you are paying with the gas flow rate. You have about the same collection efficiency overall, about the same collection efficiency with the charging case but the uncharged case increased from some 48% to 52% which isn't a great deal but we were somewhat puzzled by this static situation on the charged case. Now this test was actually run six days ago and it does not represent a large number of tests so it is of little personal value to do these over. But at any rate it appeared first in these tests that the scale-up from 140 to 1000, well actually a 700 CFM unit, would not furnish any great changes in the performance. Our residence times in these devices are on the order of 5 to 15 seconds depending on the flow rate so we are not talking about 1 second happenings. These are the same order of magnitude of that wet scrubber that you previously saw with a 50,000 CFM unit. It has a residence time about the same as this or I think a conventional precipitator has a residence time of about 5 to 10 seconds.

Now what are we going to do in the future? Almost immediately, we are working on it right now, we are going to see what is happening at the lower particle size range. As you see this cutoff here is about 0.35 microns and of course the area of interest goes as far as we are concerned all the way down to .02th and .01th so we have a Mark 4 University of Washington impactor that we have developed. We are in the process of building more specifically for such work as this so we can see what is going on across that whole small particle size range.

: What did you say your particle diameter of mass efficiency was?

Pilat: Around 3.71 micron diameter.

: If you were to quote a number for efficiency out of overall mass median diameter basis going from the particle charged droplet uncharged to both of them charged you would be increasing efficiency from about 80 to about 96%.

Pilat: For overall?

: For overall.

Pilat: That would go down here. Actually overall it went from 52 to 88%.

: For the no charge.

Pilat: For the no charges.

: Particles charged, droplets uncharged, it would be about?

Pilat: We didn't, unfortunately I didn't retrieve that information. I gather that is about it. So actually as far as this particular test that was done August 31, the difference between particle charging, droplet charging and only particle charging on overall collection efficiency is not that great. You would say maybe 75 to 80 to 88%. But I think this is the result where we are supposed to be under droplet charging and we don't have the power supply and our major droplet charge mass ratios are lower than they are supposed to be. That we don't have the power supply and our major droplet charge mass ratios are lower than they are supposed to be is where we are hurting.

: What about the power requirements in general? You said something about power return or power input?

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: What about the power requirements in general? You said something about power return or power input?

Pilat: Oh. You asked me that last year. Remember that number. I was thinking it was on the order of 1.6 horsepower per thousand cubic feet. I calculated for that previous unit which was using 15 or essentially 16 gallons per 1000 cubic feet and 100 psig pressure on the nozzle and the pressure drop across the unit, you could estimate about a half inch of water and the current flow is zilch on the actual power supply. It is finite but when we did this calculation if the gas pressure drop and the liquid pressure drop are noted; it really adds up to I would say over 9% of the power requirement.

: Could you describe your drop charging technique?

Pilat: Yes, we use an induction charging arrangement similar to what was described previously, the water droplets passing through a charged ring. Droplets are generated by a conventional spray system.

: This is not a pneumatic?

Pilat: No a regular 12 fog nozzle, commercial off-the-shelf item.

: Is the whole elevated at high voltage to charge?

Pilat: No.

: After you have formed it?

Pilat: After the drops are formed it passes through a charged ring and it actually induces the charge on that, not from it nor do we; we did not use a charged water supply like Lear described. I don't know, I think you could do it. It is just that we haven't.

: How effective is this?

Pilat: Well, we haven't actually compared the various charging. We actually selected this thicker portion and have gone with it essentially from the start as far as the induction.

: What was the demister?

Pilat: One was a sample from a supplier and the other one was, well our new one is just plain polypropylene window screen which has burned this pressure up for the efficiency and one was, I forget the name of that. It wasn't a Branch or a York or something like that. It was just a sample.

: Well, the overall pressure drop of the whole thing?

Pilat: The overall pressure drop is onward half an inch of water and it is mainly due to the demisters. We do not, we can't stand to get all water spray inside of our impactors so sometimes we actually demonstrated operating with the water pulling on through because it is a two-stage device the water will go on through and hit the next charging section and it doesn't seem to mind. It does sometimes lower our KV somewhat but then we want to do the test we stick the demister in which essentially we are including the efficiency of the demister in the whole package.

Presentation No. 4

ELECTROSTATIC CAPTURE OF PARTICLES IN FIBER BEDS

by

Dr. A. Postma
Battelle Northwest

Dreheml: We will begin the afternoon session and introduce Dr. A. Postma. Dr. Postma is currently technical leader of the Air Quality Control group at Battelle Northwest. He has been employed at Hanford since 1958. The work there is related to transport phenomena. In this time he has developed expertise in aerosol mechanics and gas absorption technology and has carried out basic studies on the deposition of aerosol particles on surfaces. He has designed aerosol sampling systems for off-gas streams, characterized gas point effluents for chemical plants and has experimentally evaluated performance of fiber beds and electrostatic wet scrubbers for removing airborne particles. He has served as technical director for a number of projects involving behavior of gases and aerosol.

Postma: I would like to talk about something a little bit different today and if it appears that I don't really understand everything that we have observed, it is probably true. I would like to talk about the electrostatic capture of particles in fiber beds rather than by falling drops.

The work to be completed will define experimentally how the removal efficiency of charge submicron aerosols depends on particle and bed properties and on the flow conditions. Three aerosols of different resistivities are being used to define the influence of the resistivity of the deposited solids while three different types of fiber beds and three different bed thicknesses are being studied. The results will define the envelope of operating conditions (flow rates, particle and bed resistivities and dust loading) under which effective removal of submicron particles can be effected.

The series of runs using a low-resistance aerosol has been almost completed. However, some anomalous results that have been obtained to date will require repetition of some of these results. Refinement of the experimental procedures have been effected and it is anticipated that the remaining runs can be performed more expeditiously. The aerosol-laden air is drawn into a 2-1/2 foot diameter duct and passes through a corona charger consisting of parallel arrangement of vertical plates and wires (three in a line). It then enters the bottom of a 6-foot diameter fiberglass chamber, 12 feet tall. The fiber bed pads may be mounted at either the 3-foot or 10-foot level of the chamber in mountings equipped to take the equivalent of either nominally an 8-square foot pad at the lower position or a 4-square foot pad at the upper position. After passing through the pad the air passes through a duct system out through an exhaust fan. The aerosol is sampled in three locations, upstream, and downstream of the corona charging section and downstream of the pad. Air flow rates through the pad are calculated from the total air flow as measured by a pitot tube velocity traverse in the outlet duct. Data collection and measuring techniques used are as follows:

Particle size:	Anderson "High Temp Stack Head" (8 stages)
Particle resistivity:	Fabricated resistance probe based on "point-plane apparatus"
Particle charge:	Filter holder used as Faraday Cage
Bed leakage:	Conducting foil surrounding side of bed grounded to picoammeter
Removal Efficiency:	Three mass samplers using membrane filters. Upstream corona charger, downstream corona charger, and downstream fiber bed.
Pressure drop:	Inclined manometer
Relative humidity:	Wet and dry bulb thermometers
Air flow rate:	Pitot tube

The ammonium chloride aerosol is generated by bubbling separate controlled flows of air through aqueous NH_4OH and aqueous HCl and mixing the two streams to form NH_4Cl. Various dust loadings are obtained by controlling the ratio of the saturated and reacted air streams and the dilution air. Particle size measurements are made primarily on sample drawn upstream of the corona charger.

Particle resistivity is obtained with a point-to-plane electrostatic deposition sampler. It is equipped with a movable plate electrode which can be moved down onto the top of the sample and is separated from the second electrode by an annular insulating ring. This ring serves to define the spacing between the measuring electrode by providing a stop for the movable plate as it is pressed down on the powder sample. A known voltage is then applied across the flat plate electrodes, and the current is measured by a microammeter. These data are the input for the calculation of the powder resistivity.

Data is obtained via the following run plan.

t = 0 min Start aerosol generation by setting the controlled flow of gas through the aqueous solutions of NH_4OH and HCl. Set corona charger at 26 KV which results in a corona current of approximately 12.5 ma. Set total flow through the apparatus as determined by a centerline pitot tube reading and checked by a complete traverse.

t = 15 min Determine the resistivity of the aerosol from an *in-situ* sample taken upstream of the corona charger. Periodically obtain a particle size measurement on a sample taken at the same location.

$t = 45$ min	Start sampling and record values of sample flow rate and pressure drop every five minutes.
$t = 75$ min	Stop sampling.
$t \approx 80$ min	Measure overall charge flux upstream and downstream of the bed.
$t \approx 90$ min	Weigh filter and impactor plates and retare.

The results of runs made to date with the ammonium chloride aerosol are provided in Tables I through III. The overall efficiency, calculated as (1-fractional penetration), is based on the sample quantity of aerosol at the inlet, upstream from the corona charger, and the outlet, downstream from the fiber bed. It includes the aerosol deposited on the plates of the corona charger. The bed efficiency is based on the downstream sample and the upstream sample between the corona charger and the fiber bed. As such it measures essentially the quantity of aerosol deposited on the fiber bed.

The variation in efficiency of both the 6-inch and 3-inch beds with air velocity is similar with a peak in efficiency observed at the intermediate velocity of 150 ft/min. No explanation for this apparent maxima is advanced at this time. Moreover, the effect of dust loading on the performance of the two beds is not consistent, and consequently these runs are currently being repeated to assure us that the apparent behavior is indeed valid. The efficiency of the 3-inch bed is lower, as one would anticipate.

The results with the stainless steel fiber bed were also as anticipated; the efficiency of the bed was very low when compared with the 6-inch polypropylene bed. However, the apparent absence of any significant removal at the high air flow rates through the stainless steel bed is also being checked.

Table I. AEROSOL DEPOSITION IN A 6-INCH POLYPROPYLENE BED

Bed Veloc. ft/min	Dust Conc. mg/m^3	Overall Efficiency, %	Bed Efficiency, %
50	9	90.8	79.7
50	26	97.9	85.5
50	56	95.1	70.6
150	7	99.3	98.7
150	23	91.8	87.0
150	53	85.6	77.8
350	10	67.3	51.4
350	28	61.7	38.5
350	74	62.8	35.5

Table II. AEROSOL DEPOSITION IN A 3-INCH POLYPROPYLENE BED

Bed Veloc. ft/min	Dust Conc. mg/m^3	Overall Efficiency, %	Bed Efficiency, %	ΔP Bed In. H_2O
50	14	78.6	5	0.01
50	30	82.9	17.7	0.01
150	10	76.3	36.7	0.11
150	21	80	48	0.20
350	6	24.3	11	0.33
350	28	37.9	10.4	0.33

Table III. AEROSOL DEPOSITION IN A 6-INCH STAINLESS STEEL BED

Bed Veloc. ft/min	Dust Conc. mg/m^3	Overall Efficiency, %	Bed Efficiency, %
50	14	85.2	18.6
350	7	42	zero
350	70	47	zero

There is some evidence that with both the 3-inch polypropylene bed and the 3-inch stainless steel bed there was some loss of initially deposited solids off the bed, particularly at the high velocities. There may be a threshold velocity at which the shear force of the passing gas upon the solids deposited on the fibers is greater than the adhesion of the particles to the fibers. This will be evaluated further.

The lower efficiency of the stainless steel bed illustrates the importance of charge effects. The higher conductivity of this bed results in charge leakage at a much lower charge level on the bed and it is believed that image forces are the only significant contributor to increased deposition of charged particles on the bed as compared to uncharged particles. The bed efficiency due to influence of image forces can be calculated from the following equations, the values for the stainless steel fiber bed being included:

$$E = 1 - e^{-\alpha}$$

$$\alpha = (4/\pi)\varepsilon_c \left(\frac{1-\varepsilon}{\varepsilon} \quad \frac{L}{d_f}\right.$$

$$\varepsilon_c = \{2 \left(\frac{K-1}{K+1}\right) \left(\frac{e^2/4\pi\varepsilon_o}{V_o d_f^2 \, \mu \, d_p}\right)\}^{1/3*}$$

d_f = fiber diameter = .03 cm = 3 x 10^{-4}m

d_p = Particle diameter = 0.22 x 10^{-4}cm

e = charge on a particle = 3.2 x 10^{-18} coul

ε_o = permeability of free space = 8.85 x 10^{-12}

ε = bed porosity = .9

μ = viscosity of the fluid = 1.837 x 10^{-5} kg/m, sec

V_o = fluid velocity = .25 m/sec (50 ft/min)

L = bed depth ∿ 15 cm.

: What pressure drop roughly are you looking at?

Postma: About half an inch of water.

: And the bed thickness?

Postma: A 6 inch bed.

: Velocity?

Postma: About 350 feet a minute.

: How much ozone are you generating?

Postma: The ozone due to the corona discharge, I guess that we really haven't measured ozone. It is obvious that there is some ozone being generated. One can smell it but I haven't studied that.

: What kind of voltage do you use?

Postma: The voltage is about 25,000 volts, a wire that is about 30 mils in diameter.

: How much collection do you get in the charger?

Postma: There is appreciable collection there. Again I haven't measured that in terms of precisely what it is but it is on the order of 20%.

: I think that it is overall.

Postma: Yes, yes it is and as a matter of fact we planned to sample downstream from the point of discharge unit to see how much that amounts to.

: Can you determine the current density that exists on those plates in the charging section?

Postma: Well, let's see. We know what current we have going through the wire.

: But then you have a set of plates.

Postma: Yes, we do. As I think about it we are talking about 20 million amps and we have I think it is 24 plates that are 2 feet by 6 inches.

: You mentioned doing some modeling. Would you care to comment at all on that?

Postma: Well, it is a little bit mysterious if you try to be honest to find a model that fits all of this. Two thoughts in mind and they are not really developed. The first is that as the particles deposit in the bed you get a space charge field developed just because the particles are in there.

: What is the relation between your wires and plates? The plates are spaced 2 inches and the wires?

Postma: Two inches apart, between the plates and vertical. There are three in series. That is right.

: The distance between the wires?

Postma: I think that is 2 inches also.

: Do you get any deposition on the plates?

Postma: Yes, we do get deposition on the plates. This is probably as I indicated 20 to 30%. The reason I can tell you it is 20 to 30% is that when we operate the system downstream wet, the overall removal efficiency for submicron particles takes the air around 50% and maybe it could be as high as 50% but it isn't that high because even if the fiber bed is wet we still get space charge precipitation within the bed and also image force charging. Just as a guess,we get from 20 to 30% deposition of particles within the corona region itself.

: Does the deposition on your plates build up gradually to a level of any stated area? What I am getting at is that you could be depositing particles and then reentraining them in the agglomerated form. This is not an uncommon phenomenon and these particles probably would agglomerate on the plates and then reentrain. This is an unreasonable method of collection and it has been done commercially but I wonder whether that is happening.

Postma: I am sure it is happening to a small degree.

: But you don't think it is, that's right. The velocity is very high.

Postma: Well, I don't think I could prevent that or some of it.

: It wouldn't necessarily be undesirable except that with another kind of a particle that doesn't agglomerate you might not get such good results.

Postma: Well, yes. I agree with you. That is really one reason we are looking at those kinds of models.

: It seems to me that if you've got that kind of a solution at Hanford for the sodium problem that there is an awful lot of money being spent on some other approaches to the sodium problem that is unnecessary That's all.

Postma: Sodium problem?

: Yes, from the breeder; sodium nitrite problem from the breeder. You guys are up to your armpits in this technology.

Postma: Well, I didn't know there was a sodium problem.

: The contractors didn't react at all for the capture of sodium and the sodium really sits inside the container. You get sodium oxide in a very very fine fume which is like you are telling us you have got here, submicron surface. They are looking for an economic way to getting it out of the shop.

Postma: Well, we have got the applications I have been involved in.

: Yes, but that's your business.

Postma: Well, not really. You can pretty much tell for yourself.

Panel Discussion No. 1

CHARGED DROPLET SCRUBBING

Moderator D. Drehmel (EPA), C. Lear (TRW),
J. Melcher (MIT), G. Penney (Carnegie-Mellon Univ.),
M. Pilat (Univ. of Washington), and A. Postma (Battelle Northwest)

Drehmel: We will begin at this time a discussion of charged droplet scrubbing. Four of these gentlemen at the table you have already met; they have given their presentations today. Also, at the table you see Gaylord Penney, Professor Emeritus from Carnegie-Mellon who did some of the original work in charged droplet scrubbing and holds some very early patents. He is generally recognized as an expert in electrostatic precipitation. With that I should explain the format. I will ask each of the gentlemen in turn to ask questions of the other gentlemen on the panel and having completed that I will throw it open to questions from the floor. With that I will ask Jim Melcher to start off.

Melcher: Yes, I think the statement that you made about Professor Penney's work is a vast understatement. Probably he should be the one to make the initial statement. I would be very curious as to how he views things overall. Do you feel we are simply trudging over the same territory again or have we made any progress?

Penney: Well, always you have got to recognize that I did this stuff thirty years ago. There was very little interest then in cleaning air as compared to now so you have opened up a whole new field. With that I have one question and one of these things that is different is something that I ran into recently. I think this morning we were all talking about trying to produce a relatively clean output gas but recently I ran into a case where the precipitator was not working and it apparently was not working because the density of very fine particles in the aerosol was so high that you almost got no corona current in the precipitator. So you have to do something ahead of the precipitator to reduce the aerosol to the point where the precipitator will work. And I wonder if that might not be an application for this charged aerosol because in that case you could charge the particles.

Melcher: This leads to one of the original comments that we have had, doesn't it? That you couldn't take the idea of neutralizing the droplets in any application. We went through that calculation for an oil ash application and came up with an effective time constant of I think it was years, extremely long, if you were to match the charged densities in that application.

Penney: That was a low density.

Melcher: Very low density. Your device is one where the charge times the density of the particulate is almost negligible. I was going to make one other comment here and that is that for me this is quite an educational thing because some of us, probably the two ends here, go at this business always comparing the electrostatic precipitators. Others of us go at it comparing the scrubbers and I think there is something very important there in getting things sorted out as to where the engineering applications are.

Lear: Well, my own charter was set up to do a comparison of electrostatic precipitators on the charged droplet scrubber concept. In other words we were asked by the EPA to do this. I believe that we originally made the recommendation to EPA that this should be done actually. I think, however, that some of us do have a combination of ESP and scrubber-type experiences and I look at it as a conglomerate. It is appropriate to look at the performance and what we have in wet scrubbers as well as electrostatic precipitators. Now I think maybe the reason we are more interested in comparisons with the electrostatic precipitators is because of the electrical requirements which we need and which you need to run with comparable efficiency. That is my interest.

Pilat: Well, I think one topic that we haven't discussed today is the performance of wet electrostatic precipitators. In other words there are a number of models where there is either a falling film or a spray in between the plates and it would be difficult for me to imagine a charged droplet scrubber having better performance of any well designed wet electrostatic precipitator with a spray because I think the field that you can generate with the wet ESP plate is much more than you can expect from a charged droplet situation so that of course is a middle of the road comparison. Perhaps instead of you comparing to precipitators and myself comparing scrubbers we ought to also compare with the wet electrostatic precipitators. If and when we get more data on them so that we will have something to compare it with.

Postma: It is hard to raise a point which may be ignorance on my part. I have seen two approaches today in treating this removal of particles by drops. One is to look at the scrubber concept and if you look at this scrubber equation the important things are drop collection efficiency from the gas ratio and look at the height from which the drops fall and the contact time itself isn't even in that equation. Dr. Melcher tells me you can't do that approach at all because of time. When you look at the residence time then thatis the factor here taken in by scrubber.

Melcher: All right. The fact is when we were comparing, this isn't a completely original discussion, we were comparing these same time constant ideas with what Mike Pilat here was putting out in experiments. Now where did he get his time for those experiments? And one thing I said at the outset is that those time constants have in them, and we agree on that I am sure, no information about inertia, no sizing, no anything having to do with impact. So what you are doing is adding a charge to the drop and saying now I am going to enhance the impact cross-section. But at some point the electric field completely dominates. You can forget that it had inertia. What I am saying is that in that limit when the electric field is dominated, you are talking about it equivalent to the time constant. I am talking about it. We can sort of go at that in certain kinds of cases. I tried to use these two particles interacting now to the exclusion of all other fields as a way of saying that. It doesn't look like two particles interacting individually that have anything to do with the number density. The charged density of each species goes back to the data of how the distance between them is related to the density of particles. It is. It is the same thing. One lesson that Ken Sachar and I had here in the last couple of months was the development of recombination of ions--plus ions, minus ions. There is something pretty general here. That is why I sort of have faith. There are lots of good results and they all seem to fit in the same framework.

Pilat: Did I understand you to say that you do not think that the Kleinschmidt (R. V. Kleinschmidt) type collection efficiency for scrubbers is applicable in a case for charged scrubbers or is that what you are asking?

: By the time it is completely dominated by the electric field, the answer has to be the same.

Pilat: It should be the same. A different approach to the same answer. Have you done both?

Melcher: No I have not. Chuck (Lear) have you?

Lear: No I haven't.

: Do I understand you that in this model you may take the total area of a particle of the water droplet in the field at its surface the bare product really gives the performance factor for the surface?

: The effective area will be quite a bit larger but you can calculate exactly what the window is and the important point out of that is that it does not depend on the relative velocity of the gas on the particle as with the essence and we have had that.

: That is the model I usually use. I was trying to think of the order of magnitude whether in that case it was good or not. And looking at Chuck (Lear) there and say what is the field and its surface and what is the velocity for it and the area times that velocity gives me the performance of the filter of the precipitator and it seems to me I can do the same thing with the water droplet and what is the field for it and the product of those two ought to give me a kind of performance. But my point was it does not depend on the velocity. The rate of charging to drops (which is tantamount to collection of particulate) does not depend on rate of velocity. Unless you reach the point where mobility times the ambient electric field is greater than these.

Pilat: So you have a reason where you feel that electrical forces, let's say forces, dominate so you can neglect these other terms and the two should agree. Yes, O.K. I think you know that taking into consideration all the forces with the part of the plate in motion due to the single droplet evaluation and so forth is more exact as long as we get the geometry of the model to agree.

: But it doesn't improve in the collection tests.

: In the scrubber model you have a term in there for either the distance drops or essentially the lifetime of the drops and you have got the terms for single drop collection efficiency. So you have got a high single drop collection efficiency but you have got a short drop lifetime. You can't plug in if you have got a 3 foot scrubber. You can't plug into the plastic model where the distance falls are 3 feet and at the same time use this high collection efficiency for the charged drops, if indeed the charged droplet lives for a few inches. The proper distance you have got to plug into the model is a couple of inches.

: You have to continually plug in the collection efficiency term that exists or the collection efficiency that the drop has to fall through the experiment.

Pilat: So we should really break the scrubber up perhaps in little volumes and aerate it on through.

: You can do an incremental study.

Pilat: What is it, I am asking a question about the lifetime electrical charge on the droplet system? In our measurement it doesn't appear to change that much from top to bottom.

Melcher: There is a little confusion in terminology because the lifetime we are talking about is how long they stay in the volume.

Pilat: I would say if we do our homework and find out the droplet's trajectory and the charge it would seem that your approaches should agree.

Melcher: They would agree but you see already this feeling is where is the bottleneck? The bottleneck isn't in how much of a cross-section a given drop has. It is how many drops are put in there. I think that is the bottleneck and that is why we point to that time constant. Now it isn't nearly so clean a thing to point at because you have brought in when you bring the inertia impact you have got another tangling of numbers.

Presentation No. 5

ELECTROSTATIC PRECIPITATOR PERFORMANCE

by

Dr. G. Nichols
Southern Research Institute

Sparks: Yesterday was devoted mostly to unconventional charged droplet scrubbers. The first two presentations today are devoted to more conventional devices, electrostatic precipitators (ESP's). Our first speaker is Grady Nichols of Southern Research Institute. Grady is an electrical engineer from MIT and before joining Southern Research he was with General Motors and NASA. At Southern Research Institute he works on ESP's.

Nichols: Electrostatic precipitators are one of a number of techniques for particulate control. Fabric filters or high energy wet scrubbers are devices that fundamentally apply the energy to the entire gas stream. A precipitator differs in that you apply energy only to the particulate you are collecting and the ions that are falling in the inter-electrode space. The ESP shows considerable promise for collecting the fine particles. We just recently had some measurements that tend to support this point of view. Superficially an electrostatic precipitator is a very simple thing. All you need to do is to put a charge on the particle and then put it in the electric field and collect it. If you go to look into it deeper you have to understand that it encompasses a number of disciplines--physics, electrical engineering, thermodynamics, and fluid dynamics. I will even admit a little chemical engineering, mechanical and civil engineering.

There are three basic steps in the process of precipitation. First you need to charge the particle. Second you need to collect it and then third you need to get it off of the plates and get rid of it, remove it. The charging business: the first thing you have to worry about is providing a

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number or a source of charge. There are naturally occurring charges almost everywhere. You could get radioactivity forming charges in the air or you could have flame ionization. You have to go to a high density free charge in order to develop a reasonable charging mechanism. The avalanche is the source of the charges in the precipitator. If you apply very high voltage to a small wire or to any electrode with a high rate of curvature, then in the vicinity of this electrode there will be high electric field that will strip electrons from neutral gas molecules.

Imagine the electric field as a function of position within the precipitator On your left-hand side you would have your corona mark coming out to the plate. The avalanche near the wire will provide carriers and the plate charge will give you an alternating electric field near the plates. So the difference in the electric field with and without current is that incremental electric field which is associated with the space charge. If we would just in our minds look back at what happens to the electron avalanche occurring within this region: there are free electrons formed and they are driven by the electric field towards the plate. So within this region of space near the wires there will be a large number of free electrons. Now within the space there would need to be electronegative gases to form the negative ions so as we would envision this electron cloud drifting across. A number of these electrons would form negative ions but as you progress there would be fewer and fewer free electrons and more and more negative ions as you proceed across. Professor Penney has discussed this a number of times when he talks about the region where free electrons may contribute to the charging. We typically think in terms of electronegative gas grabbing the free electrons to form negative ions and if this is the case it is rather straightforward to describe the charging process because you are dealing with only a single species of carriers. You know its mobility. You know its charge. In fact, in a flue gas you would have a number of electronegative gases. You would have SO_2; you would have some oxygen, some water vapor. You would have some free electrons and the thing that you need to concern yourself with in our opinion is the ratio of the different carrier species as a function of position. It leads to a rather complex analysis of the charging process but it gives you some insight as to why a measured charge is a function of position and would differ from what you might predict based on the single carrier species. Now within the precipitator there would be negative charges flowing across and these would tend to follow the electric field lines if you think in terms of that for the field gradient. And we would drive charge down to this particle, the particle becomes charged at this point. It would have a field of its own. On this side you would have the applied field being opposed by the self field and at the point where in this field goes to zero you would have no more field charging. In addition to the field charging mechanism there is also the diffusion charging. The carriers in the vicinity of your particulate have thermal velocity and even though the applied field would not give sufficient energy to impact the ion on the particle, there would be a non-zero probability that you would find an ion with sufficient energy to be driven to that particle. So your thermal velocity is the source of your diffusion charging. There have been a number of analyses of this diffusion charging business. The first ones neglected the presence of the electric field. However, as you would predict the charge on the particles from this analysis, you would find the charge there is greater than what you predict with that theory. There have been a number of people that have concerned themselves with trying to improve or upgrade this theory. They have just recently worked with predicting the charge on those fine particles better. I think there is probably room for continuing analysis of this charging mechanism because as I would see it within the vicinity of that particle, within perhaps the main free path, you would find your carriers under the influence of the electric field as well as the thermal energy. And there is reason to believe that the electric field can be significant in modifying the velocity distribution around the small particles to modify the charging carriers. Your large particles are easily collected. You have very high charge on them. Your very small particles, not only do they have a charge from diffusion charging, but also theory predicts an increase in the migration velocities so that we see a minimum collection efficiency for small particles. So this is the part; this is the region where we are looking for significance today. How to collect the fine particles?

If we now take this particle that has some charge on it and put it in the presence of an electric field, we can calculate an electrical velocity. What we have here is an example of the laminar flow case that has a gas velocity with a magnitude B and you would have an electrical velocity W and we find that the voltage trajectory for the charged particles in a case of laminar flow would be the sum. We could envision a precipitator that would have a uniform particle distribution from the inlet of a single species of particles where we got this migration of particles. We would just see the center of this pipe begin to clear as we progress down the pipe and we would collect all the particles within a given distance. If we change the particle size now and we change this migration velocity then we would have larger particles collecting in a shorter distance and smaller particles farther downstream. This idea or this technique describes rather well the behavior of the large particles. For your big particles where the input of the gas itself is small the trajectory would be fairly well described. However, as you go down to fine and finer particles to where the effect of turbulence of the gas stream is greater, we find that we tend to collect some of these particles that the turbulence remixes and we have to start again with another uniform distribution, so to speak. It is that type of analysis that led to the Deutsch equation. Rather than removing all of the particles in a characteristic distance L your concentration would reduce to like 1 over L with the fact that you keep remixing. Rather than having a region in the center of the space cleared, you just find your concentration slowly decreasing as you go down and it is an exponential relationship.

Within the region where the electrical velocity is low compared with the gas turbulent velocity, this is the region where the Deutch equation applies. Now at first you think this would complicate the problem considerably but when you are thinking in cerms of a high efficiency precipitator on the order of 99+ percent you must remove all particles that are 5 microns and larger. If we predict that the concentration of the large particles would be completely removed in this distance or drop by 1 over L and we had some 10 or 15 characteristic lengths down here, the only difference would be to predict 100% collection for the precipitator in the one case and a removal efficiency of only 99.9999% in another case. So whether you use it as an exponential or a linear analysis for those large particles is immaterial.

It is what happens to the fine particles that is going to determine your overall efficiency and it is the slip that is important.

Maybe I ought to digress just a minute here and talk about the Deutsch equation. The Deutsch equation I am talking about is 1 minus exponential of collection electrode area and volume flow rate and migration velocity. Now as this was originally derived by Deutsch he was speaking specifically of a single particle size where you know the migration velocity specifically. This equation is also used to describe the behavior of a full scale precipitator that is collecting a wide range of particle sizes. If you go to a power station and you make measurements on a precipitator for a number of velocities and you come out and you are going to apply efficiency as a function of volume flow rate you will find that, you know, this equation describes the behavior rather well as long as you restrict yourself to small variations in the velocity. It is only when you have large variations in velocity that a deviation occurs and this is fundamentally because you are dealing not with a single character of a single particle size, but you are dealing with a spectrum of particle sizes each one of which has a different migration point.

The next thing in the list of behavior of precipitators is the dust removal business. You collect a layer of dust on your collection electrodes and you must get them out and typically you do this with either a drop hammer, vibrator or some method for getting dust off the plate. We can envision these large plates some 30 feet high with a dust layer in the neighborhood of 0.5 centimeter to 1.5 centimeters and you have to drop this off and get it in a hopper.

The next thing of significance to us is the electrical behavior of the precipitator. What you have is a small central electrode with some 50,000 volts applied to it and some collection electrodes some distance away. I measure current and applied voltage in kilovolts. As you increase the voltage your current will follow the clean plate curve for a precipitator. Now, let's add a dust layer. You put a dust layer on this precipitator. It has a low resistivity on the order of 10^7 ohm-centimeters. Now this is a pretty good dust layer and really it looks like you have just moved the plates a little closer to the wire when we do this. You would have the same positive surface charge on your dust layer that your metal plate would have and if we redraw the curve now applying the voltage it would just shift the characteristics towards a little higher current for each voltage. You have just narrowed the spacing. If instead of this highly conductive dust layer we would put one on with resistivity on the order of 10^{+10} or 10^{+11} ohm-centimeters we would now have not only the voltage drop in the leftover electrical space, we would now have additional voltage across the dust layer. What we have now is our normal curve we started with but in addition we have a voltage drop across the dust layer. It is going to shift the curve.

Let's take another step now and we are going to put a highly resistive dust layer on there, a very highly resistive dust layer. Now as we start to bring our voltage up, since the resistivity is high, we will have a very large voltage drop within that dust layer. We came out with charged particles that did what they were supposed to do. If you envision what happens over the plate under the same conditions and you have a corona it is going to give you the wrong ion back and when you get negative charges going in this direction, corona at the plate will give you positive charges that drift back and do your precipitator in. See if you agree with what happens. These take turns and drive the voltage up to where we get a spark. The spark will be determined by the plate spacing and the carrier species in your gas. Inducting or low resistivity gas wouldn't change the precipitator behavior much at all. It would just go along the way it is.

O. K. We will describe rather well how a precipitator behaves and its actual behavior is computed by the fact that you have a large size distribution You have a number of carriers and a number of particles that range from 50 microns down to the tenth micron range and you can understand how any one of th size ranges would behave. But in order to envision how it behaves as you progress to the precipitator with the influx of a large number of sizes, it just leads to confusion if you are trying to calculate. So in order to handle this we developed a computer model of a precipitator and what we feed into this model are the characteristics of the dust, size distribution, resistivity if you know it, current density of applied voltage, and from this you can calculate the charge on the particles, the electric field as a function of position from the wire to the plate and the dust concentration within each of the size bands in the inlet of the precipitator. Envision yourself calculating that migration velocity when you know the charge of the particles and the field and the concentration, you can envision what happens to each size integral as you progress through the precipitator. And this is what we attempted to do with a computer model. Now we made a good bit of progress with it. O. K. Now it describes how the computer would predict the behavior of the precipitator, for two different electric field conditions. The result of this would be that you could predict for your precipitator the collection efficiency as a function of this thing called specific collection electrode here and this is square feet of collection plate per 1000 CFM gas flow. A low current density would be operating with what we would expect from a high resistivity dust; your voltage would be low; your current would be low. Your charging conditions would be not good and we would predict 90% efficiency for a size of about 150 square feet per 1000 CFM. You twist around to an intermediate resistivity dust for the same size we would predict some 95% efficiency and we would build it around to some value of 700 or 800 square feet which are some of the current design sizes for those western fly ashes.

O. K. Let's for a minute spend a little time on what limits the performance of the precipitator. You saw what the high resistivity did to you. It causes you to operate at lower voltage and at lower current. How do you collect high resistive material? Well, you take the brute force technique and just build a large precipitator. If you determine that it took 800 square feet per 1000 CFM you just reach back under here and you bring that ten million dollars out and you buy you one. The other approach you might take is O. K., I have a precipitator and I am going to worry about changing its resistivity and I can buy some sulfuric acid and dump it on my troops. I can change the resistivity and live with my normally sized precipitator and worry with operating the chemical plant. We could change the resistivity another way. We could move our precipitator somewhere in the process where the temperature is higher. We found that when we got up to temperatures in the range of 700°F that the bulk resistivity was low. We didn't care what the surface material was, so we could move our precipitator prior to the air heater in a power station and operate hot side. The only thing you pay for here is the added gas volume flow rate. At 700°F as opposed to 300 you have about 50% more gas to handle. Another thing we might do is get cold. If you cool it down to where you have some moisture, you are near the moisture dew point, you want to put sulfuric acid on the layer, you will put moisture on the surface of the dust and this can provide a conducting path. This has been done. I understand that the control of the temperature gets to be rather tight. If you get too cold it will get wet and close up on you. The next thing you could do is you could put in a wet ESP. If you swept off the dust layer as it got on the plates then the effect of your high resistivity would be reduced.

: What is the approximate residence time of the gas?

Nichols: 7 seconds.

: Does this include rapping?

Nichols: That includes rapping. The precipitator is operating normally.

: What about the limestone addition...?

Nichols: The limestone addition would do you in for efficiency. What it would do if it is going to scrub SO_2 is scrub out SO_3, so you would have very little conditioning and your resistivity would be high and you would have to build that large size box I am talking about. It takes the SO_3 out if I understand the value of it.

: How do you take care of a transfer of the dust from the plates to the hopper in your computer model?

Nichols: I knew you would do that to me. I don't know how to handle it. We have the capability for including the percentage of each of the size fractions being reentrained and we have tried it with a variety of numbers like 10% that was collected reentrained up to 40%. If you are going to have a 99.6% precipitator you have got to have your rapping losses very low. You must have your range very low.

Presentation No. 6

THE DUST LAYER AND PRECIPITATOR EFFICIENCY

Prof. G. Penney
Carnegie-Mellon University

Sparks: Our next speaker is Professor Penney who was introduced yesterday so I won't use any of his time. Just let him talk.

Penney: The precipitators look simple but I think anybody who has worked with them knows that they are not simple and so it is easy to talk on and on. I want to touch some high points.

This project was initiated to study adhesion of the layer of precipitated dust. There was interest in 2-stage precipitation for removing flyash and similar dusts. However in a 2-stage precipitator electrostatic forces deposit the dust but then the electrostatic force reverses and tends to pull the particle off. Thus in 2-stage precipitation the particles must be held by adhesion. It was obvious that there was something peculiar in this adhesion since on the electrode the dust can exhibit a high adhesion and yet if it is removed from the electrode and pressed at 1000#/in^2 there is no apparent adhesion at all.

About this time work supported by the National Science Foundation disclosed that the action of a dust layer in initiating a spark could be imitated by clean point-to plane electrodes and electronic circuits. This could be subject to exact control and so made it feasible to study this kind of spark. So the study of sparkover became a large part of our work.

I first want to mention some older mechanisms for initiating sparks. In the early 1900's Townsend advanced a theory of breakdown. His theory depends on a naturally occurring electron at the cathode. At breakdown voltage this

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electron is driven by the field and knocks off another electron from a gas molecule. Thus there are two electrons which can liberate two more. Thus the process builds up and in a 1 cm gap can form a few million ion paths in crossing the gap. But this would be just a minute pulse of current. Something must liberate another electron at the cathode to keep the process going. Townsend first proposed that the positive ions in striking the cathode released electrons from the cathode. This was found to be a false assumption. So he proposed that photoionization or photoemission could be this secondary mechanism. We now know that this is true and that the Townsend mechanism accounts for the breakdown of uniform fields at around 30 KV/cm. However it cannot account for the sparking in precipitators at a fraction of this field. Loeb and Raether and their students studied what they called "streamers." These were produced by abruptly applying a high positive potential to the point of a point-to-plane gap. This may result in sparkover of a 5 cm gap at about 50 KV or about an average gradient of 10 KV/cm. But this is much higher than the voltage at which precipitators are observed to spark over.

Work in our laboratory showed that with high resistivity dusts the corona current can result in a series of minute sparks. These trigger a series of discharges each resembling the individual discharges which Loeb and Raether had called streamers. If these streamers repeat at the proper frequency (about 30 KC) they result in breakdown at about 5 KV/cm at atmospheric pressure and temperature and a still lower voltage at elevated temperature. In these streamer discharges and with proper instrumentation one can observe a spot of light which travels from anode to cathode at a velocity of the order of 10^8 cm/sec. It is generally agreed that accompanying this spot of light there is a concentration of positive ions which produces a strong but local electric field.

This spot of light travels in the direction that positive ions move but the velocity is 10,000 times the velocity that individual + ions could travel. Thus, this concentration of + ions traveling with the spot of light cannot be the motion of a given group of ions but rather is a wave-like phenomenon in which ions are continually formed in the direction of travel. Qualitatively this is explained because electrons are released ahead of the spot by photoionization. These electrons are accelerated by the high local field so that new ions are formed ahead of the old group and the electrons move back to neutralize the old ones. The puzzle lies in subtle questions of stability. Why do successive discharges build up in some cases and not in others? What determines the size of the group or concentration of positive ions? What causes it to sometimes branch in all directions and sometimes to move ahead in a relatively straight line? These and many similar questions are unanswered. In one set of data the current builds up to its peak in 1/10 microseconds and decays to 1 ma in 0.4μ sec. Streamers may vary from 10 ma to 100 or 200 ma but time to a peak and the decay time are almost the same.

In another case the streamers were occurring at a rate of about 6000 per second. This is too slow for the build-up to sparkover to occur. So that all pulses are of about equal intensity. Here we see a superposition of about 1000 individual streamers. Each individual streamer is characterized by a spot of light traveling from anode to cathode. Frequently branching occurs, so several spots of light may develop. But primarily what we see here are various streamers following somewhat different paths. This is often called a flare or brush.

If the repetition rate is increased to 30,000 per second then successive streamers tend to follow the same path and as I will describe in a minute gradually form a hot channel which starts at the anode and builds up toward the cathode until sparkover occurs.

In any given train the repetition rate is 30,000/sec. so that the current becomes successively higher. Each train consists of 20 pulses. It is interrupted after the 20th pulse so that sparkover does not occur. The trains are repeated at 50/sec. which is slow enough so that each train is independent of the preceding train. A is the first pulse which repeats almost exactly. The 6th pulse is shown at B. The current is higher but the individual pulse trains do not repeat as exactly so we see a shaded area.

The twelfth pulse is shown at C and here the current has about doubled.

The 20th pulse is shown at D. The peak current has increased 2-1/2 times, with considerable variation from pulse train to pulse train.

The applied voltage was about 5 KV higher than the minimum required to produce sparkover.

Sparkover would have occurred in a few more pulses if it had not been interrupted.

An article to be published in the January issue of the Journal of Applied Physics describes tests made by John Geary. He used an ingenious combination of moving and stationary mirrors to scan a streamer discharge using a coherent beam of laser light. Then interferometry was used to measure the phase displacement of the part of the beam which had traversed the discharge. Heating of the air would result in phase displacement which could be measured. This slide shows temperatures computed from his measurements.

The lower plot is reproduced from the oscillogram. We see current pulses from successive streamers which increase successively. The arrows show the times at which the five scans were made. These successive scans are made near the point in the point-to-plane gap. We see that the first scan after the second streamer shows a small increase in temperature. Scanning the channel a little later shows a still higher temperature and so on. Until the fifth scan which is near the point of sparkover shows an increase in temperature of about 250°C. This nearly doubles the absolute temperature, thus halving the density. Halving the density permits sparkover at one-half the voltage. This is in agreement with our observation of sparkover at 5 KV/cm, as compared to Loeb's 10 KV/cm for a single streamer.

Remember that these scans were made near the point. Other similar measurements made near the cathode showed no increase in temperature until near the end of the pulse train. The spot of light traversed the entire distance and we had supposed that any increase in temperature would occur in the entire channel.

Geary followed this by developing photographic techniques to photograph streamers at controlled times in a pulse train. These photographs showed that the spots of light traversed the entire distance. But that the increase in temperature started at the point or anode and gradually progressed across the gap. When the hot channel approached the cathode the gap was ready to spark over. But sometimes in a pulse train streamer branching occurred and the build-up process collapsed. Thus there are still many unanswered questions as to the mechanism and particularly to the stabili of the streamer as it progresses across the gap.

In industrial precipitation we are seldom removing dust from air. We are almost always dealing with mixtures of gases. The water vapor content is usually higher than in normal air. In some process work the gas may be mainly water vapor. Water on the surface of an insulator is relatively conducting and so it might be assumed that water vapor in air would lower the sparkover voltage but such is not the case.

Tests made by Larry Schmitz were made at 100°C so that the water vapor content could be varied from zero to 100%. B is the sparkover for a short gap (1/2") and A is for a longer gap (1").

For the shorter gap the sparking voltage for 50% water vapor is 2.4 times that for dry air. For the longer gap the effect is even greater, only 28% water vapor being required to double the sparking voltage.

It might seem that this effect of water vapor would be common to all types of sparking, but such is not the case.

The Townsend breakdown for uniform fields does increase with water vapor content. But it shows its greatest increase in sparking voltage from zero to 1% water vapor where this curve shows a minimum at 1%. But beyond 1% water vapor the Townsend type of breakdown shows a slow increase so that at 50% water vapor the increase in voltage is only 16%.

This illustrates the complexity of sparkover with mixtures of gases. With the Townsend type of breakdown nitrogen, oxygen and air have nearly the same breakdown voltage. However, with the repetitive streamer type of breakdown they behave very differently. In my opinion the question of sparking in mixtures of gases is a very important area for further study.

A serious handicap to precipitator development has been the fact that pilot-sized precipitators could not predict the performance of full-sized units. In particular the operating voltage of the small unit would be much higher even though the interelectrode distance was identical. White, in his book,cites a classic example of varying numbers of identical pipe type units each 8" ID by 16' long. Thus each unit consists of a wire inside of an 8" ID pipe 15' long. With only one unit connected the sparkover voltage was 86 KV. With two connected in parallel the voltage dropped from 86 to 85 KV. With five units connected the voltage dropped to 80 KV. Connecting 91 pipes dropped the voltage to 57 KV or 2/3 of the 86 KV carried by one unit. Since the drift velocity varies as a power of the operating voltage it is obvious that a 33% drop in voltage gives a very serious reduction in performance.

Dust layers are so variable that it would be very time consuming to determine probability of sparkover for a wide range of conditions in an actual precipitator. However since we can use point-to-plane electrodes and electronic circuits to imitate the initiation of a spark by a dust layer, it became practical to study a wide range of circuit parameters.

When one connects precipitator elements in parallel, an obvious effect is to increase the capacitance which must be discharged through any spark which occurs. This slide shows the results of tests by William Collins to study the effect of circuit capacitance on the probability of sparkover as a function of voltage. Using a given train of pulses and a given capacitance he could measure probability of sparkover as a function of voltage. He could then repeat the test with a different value of capacitance and so on. This shows results of a number of tests. 125 picofarads would correspond to a laboratory precipitator and 20,000 pF to a full-sized unit.

Probably a more important parameter than capacitance is the probability of sparking as a function of precipitator size. Since the cause of sparking is a defect or electrical puncture of the dust layer, this cause tends to be proportional to area of collecting surface.

A typical way to operate a precipitator is at a given number of sparks per minute. For a laboratory unit with a few square feet of area and a low capacitance, this is a high probability per unit area. On the other hand, for a large unit with a high capacitance and 5000 to 10,000 square feet this same 5 sparks per minute is a very low probability of sparkover per square foot of area or far off to the lower left of this curve thus the indicated difference in voltage is large.

So we are quite optimistic that by duplicating circuit parameters in a pilot-sized precipitator and by properly scaling the probability of sparkover, we should be able to make reasonable predictions of the operating voltage of a full-sized precipitator from tests on a small unit. We are looking for an opportunity to test this theory.

The study of sparkover has improved our understanding of precipitators and hopefully will enable a much better prediction of performance in a new situation. But unfortunately it has not led to any breakthrough to markedly improve precipitator performance.

Fromthe standpoint of improving precipitator performance, the adhesive properties of dust and the transfer of dust from the collecting electrode to the hopper seems to me to be a more promising area for investigation. However it is a very difficult area to study analytically.

In a precipitator thick layers of dust often build up. Looking into a precipitator after a long period of operation one often sees dust deposits of over 2 cm thickness. But these are very irregular, apparently because dust breaks off in irregular fashion. This slide illustrates a small area where dust has broken off.

Corona current must be conducted through the layer of collected dust. It can do this until the breakdown voltage of the dust is reached which is typically 10,000 to 20,000 volts/cm. At this point minute sparks occur through the dust layer. This causes back-corona, and may trigger streamer pulses which result in sparkover.

Suppose the resistivity of the dust is 10^{12} ohm-cm and its puncture voltage is 15 KV/cm. Then the permissible current $I = \frac{E}{R}$ is $\frac{1.5 \times 10^4}{10^{12}}$ or 1.5×10^{-8} A/cm. Suppose one adjusted the corona current to this value. Then the voltage drop in a 2 cm layer would be 15 KV/cm or 30 KV, while in the adjacent 1 mm thickness it would be 1.5 KV. It is obvious that such a drop would seriously distort the electric field so that the current density would not be uniform. Current would concentrate at this thin dust layer so that the average current density would have to be reduced to avoid back-corona.

Probably a more serious handicap is the fact that in a large precipitator dust near the top of the electrode must fall 25 or 30 feet to reach the hopper. It must fall transverse to the air stream and so much of the dust is reentrained. To avoid visible puffs, so called "continuous rapping" has been used, but this is very inefficient in removing dust from the plates.

In addition to theoretical objections to thick dust deposits there is the practical experience that precipitators operate relatively efficiently for a few hours after being shut down and thoroughly cleaned out. From such reasoning one can make a strong case for mechanically as well as electrically sectionalizing a precipitator. In this way a section could be dampered off and vigorously rapped to remove any heavy dust deposits without reentrainment. This would of course add to the cost for a given size. So information on the possible gain is needed to indicate whether the cost can be justified by the improved performance. This indicates a need for more basic work on adhesion.

Early in our investigation, E. H. Klingler developed means for measuring adhesive forces in deposited dust. We developed a theory of adhesion based on differences in work function and contact potentials over the surface of a particle.

But there are many complications in the theory and in the behavior of the dust deposit. Measurements of contact potential of the dust deposit show that this field changes with time and often reverses within a few hours. This reversal is similar to the reversal of the field of electrets. Electrets have been studied extensively by physicists. They have developed a theory that the electret consists of a combination of fixed dipoles and mobile charges and that the mobile charges account for the changes in the external field. The behavior of electrets and of electrostatically deposited dust seems to have many similarities.

The paper by Klingler and myself described our first tests. In these tests we did not find a method of getting high adhesion in the mechanically deposited dust and we were careless in not describing our method of mechanical deposition.

Later Niedra tried various methods of depositing dust and found several mechanical methods which could produce as high adhesion as electrically deposited dust. We attributed the high adhesion to rather random distribution of contact potential differences over the particle surface. Niedra also found that most dusts were not the simple dipoles which Klingler happened to work with and so the alignment by an electric field was very limited.

Dalmon and Tidy (J. Dalmon and D. Tidy) at Leatherhead measured adhesion of dust and found high adhesion in mechanically deposited dust. Of course this appears to be in conflict with our first paper. So they say we are all wrong. But unfortunately, like the Klingler paper, they did not give details of their method of mechanical deposition.

Dalmon and Tidy also point out that interruping the current during electrostatic deposition can produce a weak interface and so could account for the weak interface when the polarity was removed. We also found this but unfortunately did not describe the procedure followed to eliminate the trouble.

It appears that much of the disagreement occurred because they had not seen our second paper.

O. J. Tassicker in Australia has been studying adhesion. Thus far he has been attempting to explain adhesion by van der Waals forces. We recently had a chance to talk for a few hours and I believe he agrees that van der Waals forces cannot account for many of the phenomena observed.

In this brief discussion I can only mention a few high spots. As I see it Dalmon and Tidy have not disproven our theory but obviously neither have we proven the theory.

So much remains to be done to adequately explain the behavior of the collected dust.

Why concern ourselves with any theory? In my opinion this is needed to understand rapping and the falling of dust. Rapping force is often specified in maximum acceleration (G's) without regard to frequency or amplitude. If there is an organized orientation of the particles, then amplitude of motion is important as well as the peak acceleration and this will vary from dust to dust.

One may argue that we merely need to make empirical tests and then copy the best behavior. But it is my belief that precipitator performance is too complicated for this method to be successful. If we do not understand the basic mechanisms, mistakes in interpreting empirical tests are almost certain to occur. White in discussing precipitator energization says, "An empirical approach to the question merely leads to hopeless confusion because field data, when presented uncritically, may be cited to support almost any point or conclusion."

There are other definitive tests that can be made to distinguish between theories and to evaluate the extent to which a given theory applies. I believe that such fundamental or basic research should be conducted in parallel with the empirical tests so that results of both can be compared.

: Why is the probability of sparking tied in with the capacity?

Penney: Because you get these pulses of current.

deposited dust and we were careless in not describing our method of mechanical deposition.

Later Niedra tried various methods of depositing dust and found several mechanical methods which could produce as high adhesion as electrically deposited dust. We attributed the high adhesion to rather random distribution of contact potential differences over the particle surface. Niedra also found that most dusts were not the simple dipoles which Klingler happened to work with and so the alignment by an electric field was very limited.

Dalmon and Tidy (J. Dalmon and D. Tidy) at Leatherhead measured adhesion of dust and found high adhesion in mechanically deposited dust. Of course this appears to be in conflict with our first paper. So they say we are all wrong. But unfortunately, like the Klingler paper, they did not give details of their method of mechanical deposition.

Dalmon and Tidy also point out that interruping the current during electrostatic deposition can produce a weak interface and so could account for the weak interface when the polarity was removed. We also found this but unfortunately did not describe the procedure followed to eliminate the trouble.

It appears that much of the disagreement occurred because they had not seen our second paper.

O. J. Tassicker in Australia has been studying adhesion. Thus far he has been attempting to explain adhesion by van der Waals forces. We recently had a chance to talk for a few hours and I believe he agrees that van der Waals forces cannot account for many of the phenomena observed.

In this brief discussion I can only mention a few high spots. As I see it Dalmon and Tidy have not disproven our theory but obviously neither have we proven the theory.

So much remains to be done to adequately explain the behavior of the collected dust.

Why concern ourselves with any theory? In my opinion this is needed to understand rapping and the falling of dust. Rapping force is often specified in maximum acceleration (G's) without regard to frequency or amplitude. If there is an organized orientation of the particles, then amplitude of motion is important as well as the peak acceleration and this will vary from dust to dust.

One may argue that we merely need to make empirical tests and then copy the best behavior. But it is my belief that precipitator performance is too complicated for this method to be successful. If we do not understand the basic mechanisms, mistakes in interpreting empirical tests are almost certain to occur. White in discussing precipitator energization says, "An empirical approach to the question merely leads to hopeless confusion because field data, when presented uncritically, may be cited to support almost any point or conclusion."

There are other definitive tests that can be made to distinguish between theories and to evaluate the extent to which a given theory applies. I believe that such fundamental or basic research should be conducted in parallel with the empirical tests so that results of both can be compared.

: Why is the probability of sparking tied in with the capacity?

Penney: Because you get these pulses of current.

: Professor Penney, there was a paper given at the Underground Transmission Conference and I am sure you heard about it. Somebody had made a study on the random nature of breakdown of very high potential AC gas dielectric conductors and I think he just simply said it was a completely random situation and that your probability there for increase with the area over which you are looking at it. You could almost explain the same phenomenon here by saying that, rather than having its capacity affected.

Penney: We tried the same thing with voltage. The capacity effect is important and in his tests the curve ratio has different pulse strengths. But in addition to that, first there is the size question in the precipitator. So these efforts at any given square foot have some small probability of helping. Ionization tends to be mostly, most of these breakthroughs tend to be kind of staged. It is only occasionally that you get pulses at the right frequency. It is kind of an improbable effect at any given square foot. So if you have got a small precipitator and you operate at 5 sparks per minute, there is a very high probability that any given square foot has to do the right thing to produce sparkover; whereas, if you get a big precipitator and operate at the same 5 sparks per minute, it is a very low probability after taking into account what the current is producing. The difference is between the large and small precipitator.

: I think this maldistribution, current distribution.
If I understand it the dust tends to concentrate at very definite points, sometimes widely separated, and you can get very high current density which...

And therefore a dust problem.

Penney: So it seems to me that one of the big weaknesses of this continuous rapping is that you get these heavy deposits but you can't hit it hard because then you get deposits.

: Are you supposed to do that at night? Would you comment just a little bit about those temperature measurements?

Penney: The scan that I showed you was very uniform. In the space between the points. The point was here and the plate here. The first scan was the one that I showed you was very near the point. Now I didn't take time to show a similar thing, he made scans halfway between.

: And this was in static air?

Penney: In static air. And when you got nearer the plate then you didn't see any increase in temperature until you got very near the end of the pulse train, very near the sparkover. That was contrary to what we were expecting because we had expected to observe a spot of light going on every time that the voltage was being reduced. So we expected the increase in temperature to occur also but it appears that the buildup of temperature sparks back at the point and just gradually progressed.

: Did you measure the gas temperature?

Penney: The gas temperature--the local temperature.

Presentation No. 7

FRACTIONAL EFFICIENCY OF ELECTROSTATIC PRECIPITATORS

Mr. J. McCain
Southern Research Institute

Sparks: Our next speaker is going to talk about a subject that everybody here has run into--how you measure the efficiency of one of these devices so you know what you are doing. Joe McCain is with Southern Research Institute. He has been working on measuring particle size and precipitator efficiency for the last couple of years.

McCain: I am going to describe today not so much the results of field tests although I will give a few samples. In fact I was just remarking that what looks like an extended field program keeps getting longer and longer when you try to measure particle size distribution. But several techniques have been used in the past to measure size distribution into control devices and we have used most of what is available. I won't say we have come close to using all of them. One method is collecting filter samples and you examine the samples at a microscope or scanning SEM or something and count the particles. It is tedious but it gets numbers. Filter samples obtained that way frequently can cause an overloading problem with just the number density. You are looking at a very short time exposure snapshot of the process and it is hard to tell anything about the long term variations or time dependent things.

Other devices that we have used include impactors, condensation nuclei counters, diffusion batteries, optical particle counters, that is light counters, single force counters and we have made a light fuse or tried one of Whitby's (K.T. Whitby) aerosol analyzers, electrical mobility analyzers, but he doesn't have one available that is particularly adapted for stack use at the moment and we are not too concerned with ambient air.

Physical size distribution going into those control devices, this is on a mass basis, ranges over a fairly broad range of mean sizes and geometric standard deviation. Some of the things that we have tested: coal-fired electric generating stations (and more of them than I can count on my fingers and toes I think), sulfate pulp mill recovery units, and sulfite pulp mill recovery units, well we have got some slide efficiencies on a pilot-scale device, on an SO_2 absorber, sulfite and SO_2 absorbers themselves, several types. They produce a rather fine potential for mean size and size in the range of about 1/4 of a micron--nice blue haze with grain loadings on the SO_2 absorber frequently very low, mass emission rates of something like 0.02 grains per cubic foot. But in the visible emissions, because of the concentration of the particulate in the region in which sparking is especially active optically, you make quite visible fumes of blue haze that have pervaded the neighborhood and are at least a visible nuisance.

Some of the devices that we have used in stack sampling are inertial separators, such as modified Brink cascading impactors (with cyclones mounted externally to remove foreign particles that tend to overload the first stages) and an Andersen impactor with a cyclone for the same purpose. The Brink impactor as manufactured is intended to be used external to the stack. We have modified several ourselves and Bruce Harris (CSL's D. B. Harris) here at EPA has modified a couple. Some people have used some of our cyclone design, not to be confused with instack samplers. Instack sampling is always preferred. You get the material as it exists in the gas stream with no probe losses, no problem of condensation in the probe.

Another inertial separator is a multiple cyclone, good for collecting bulk samples primarily. The separator itself is outside the stack and is a fairly large bulky device.

A question was asked by someone yesterday about do you believe impactor data. Three of us that I know here use them regularly but nobody jumped up and said "Yes." There are problems with impactors. I will illustrate one that has been noted by some people in their work and didn't bother them. It turns out that it should have. These are plates with the Brink impactor. I will show you some in a moment run under different conditions with just one change in the materials being collected in which the material which should be deposited right in the center of each of these plates obviously is not here. It is scoured clean under the jets and there is material on the plates but it is in the periphery. Full micrographs of the material on these plates showed that everything from here down looks just alike. Every stage and the filter all look alike so that in terms of the sizes of the material and colors it obviously is not fractionating properly. You can weigh these things and assume you have done the job and you are going to have erroneous data. Just a few minutes in time separated that series from this series--the difference being that both of these were done at a TVA coal-fired steam plant, a few minutes apart. In this case about 10 to 20 parts per million ammonia was being injected into the flue gas as a conditioning agent upstream of the measurement point. The impactors were run at the same temperature, at the same location and at about the same flow rate, plant load and everything has not changed. The only change in conditions was the injection of ammonia. In this case a moderate sulfur coal produced a fairly reasonable SO_3 concentration which reacted with the ammonia to produce ammonium sulfate fine particulate which we were measuring concurrently with CN counters. Fine particles of ammonium sulfate apparently coated the surfaces of the flyash changing the adhesion quality of flyash. Thus, deposition has not taken place on the impaction site you would expect and as they should. So in this case it was a problem of getting reasonable data. So in answer to the question about do you believe impactor data, we have got to ask under what conditions was it obtained and a number of other things. How was the impactor operated under those conditions? The same impactor operated this way in these two cases: one case you can believe, probably; the other case, you can't. It is one of several things that need to be examined. A lot of those impactors are run with bare metal substrates. They work fine provided velocity doesn't exceed something like 35 meters per second, jet velocities. Velocities above that, particles tend to bounce. They don't adhere to the plates, particularly things like fly ash or silicate and you get effects like this.

The condensation nuclei counter (CNC) operates by saturating a gas stream with some vapor. Principally, the one we used first was water but alcohol had been used for other things. By cooling with water, or some mechanism for supersaturation which results in condensation of the vapor on the surface of the particle, the particles grow to some much larger size in which they could be detected visually. Under 0.1 micron particles it is all but impossible to detect optically. Five micron particles are fairly easy to detect optically so you in some way grow the particle by condensation from 0.01 micron to 5 microns and then you can detect it. Sizing can be done crudely with this type device by varying the supersaturation achieved. The critical diameter or radius for nucleation depends on the supersaturation achieved. Less supersaturation condensation will take place only on larger particles and you increase the amount of supersaturation achieved and condensation takes place briskly on smaller and smaller particles. But there is a rather strong solubility effect. Your soluble particles at the same size will more readily act as condensation sites than insoluble particles. This is not a particularly good way to size although it will work, especially if you are dealing with either wholly soluble or wholly insoluble material. In the case of this device, water in the airstream is supersaturated cooled a little bit and the light scattered by the fog gives the measured amount of fine particles present. This device achieved about 10 to 15% supersaturation. There are some commercial devices made by Environment One and by General Electric Research Labs that achieved supersaturation by expansion. They will detect particles down to size something like 0.002 of a micron. The lower size limit is determined more by the diffusional losses in the sampling line than by the expansion process itself. We have used some General Electric counters and Environment One counters for field work. Using the counter as a detector and diffusional batteries, the size distribution can range from 0.2 micron down to about 0.05 micron. Stack gas concentrations typically run to something like 3 or 4 orders of magnitude above the limits for CNC optical particle counters. So it requires extensive dilution in order to use these techniques. This is the basic scheme of our diluter pollution system which we are using with the optical and condensation nuclei counters. Currently I am using a cyclone to eliminate large particles which tend to clog the metering orifices. The diluter is a cone where the sample is put into the center. The cone is perforated with sets of concentric jets starting at close to the apex of the cone. The jets are aimed for each set of concentric jets and the jets range in opposite direction so they produce a swirled counter-swirl kind of thing. A very turbulent mixing cone. Up to about 3 or 4 microns it is mixed to the point where you can take a traverse across the body of the diluter about 4 inches in diameter here and get essentially uniform concentration all the way across the body. The flow mix is diluted. The metering orifice in this line is for adjusting the amount of dilution air and internal pressure through the body. This flow rate typically for the sample is 10 to 4 liters per minute and the flow rate of addition air stream is typically 200 liters a minute. So we are achieving dilution factors ranging from something like 50 to 1 to 2000 to 1. This brings the concentration in the stack down to the point where the instrument will operate reasonably well.

Presentation No. 8

ELECTRIC ARC GENERATION OF METAL AEROSOLS IN QUANTITY

by

Prof. B. Linsky and Mr. R. Hedden
West Virginia University
and
Illinois State Air Pollution Control Agency

Sparks: Our final paper is on probably the first thought that everybody trying to do research on particulates runs into: how you make an aerosol so you can test your equipment? Professor Ben Linsky from West Virginia University and Robert Hedden from Illinois State Air Pollution Control Agency are going to tell us about one solution to the problem of generating aerosols.

Linsky: Thank you. The broad purpose of our development was not just to provide a feeder for an experimental control device that is realistic and that would represent the real life out there. The origin and purpose are a little more involved than that and I would like to give you the foundation for it if we can take a minute for it. The actual description of what we have done so far, what our plans are, where we are going Bob Hedden will present. He developed it. He did the work as a graduate student and is now one of my alumni. He is a consultant on a research grant that will be able to get brownie points and credit as well as enjoy the fun of getting some work, getting further work done, that ordinarily alumni don't get a chance to do. So we are lucky we were able to work this out.

This started back in '58. The emission inventory in the San Francisco Bay Area Air Pollution Control District provided a set of total particulates in tons per day in the different kinds of polluting operations and different types of polluting operations by the size breakdown. I have forgotten now; I didn't look it up again, zero to 5, 5 to 20 and above, I think it was. You can see a copy of it in the 1958 Proceedings of the National Conference on Air Pollution in Washington with the Surgeon General at that time. The reason for showing the breakdown--by the way we labelled our data A, B, and C--A was firm data, B was fair data and C was estimates, clearly labelled. The firm data I am not so sure that that was that firm, but it was the best; it was our best judgment at the time and a review by our peers around the country because we had a lot of branch plants out in the San Francisco Bay Area. They didn't like it, the polluters, and this is a reason for doing what we are doing, one of the reasons--because we had to start focussing in on the small particles. Now we are talking 99%. We are not talking everything. We are talking 85% or 90% of the small particles. Total particulates that will range from 20 microns and above all that gravel, what does that do except fall on the roof, but it is the small stuff that we are concerned about. It has been difficult to catch and also in its effects. So coming in from the effect side now we began to get at some factors. I knew from my occupation in health work back when, before I was an air polluter, that fresh metal fume caused tougher biological reactions than did aged metal fumes like zinc oxide. The stuff that you shook off the rafters didn't cause as much trouble as the fresh stuff and what happened while it is going from fresh to aged, apparently there is not much literature, not much known about it. So it was necessary in the beginning to do research on collectors that would catch the small particles to produce a way of, to have a method of producing small particles hopefully in predictable size ranges, particular size spectrum. And that is what we got at. Biologically I suppose we could say that there is a difference between stale bread and fresh bread. For all I know stale bread may be better for you but at least there is some of that kind of qualitative difference of hydrolization and a few other things that happen on the surface of a particle, especially on the tremendous acreage of a kilogram of big particles.

The same kind of effect may be involved in electrostatifying stuff either dry or wet. We don't know and I don't know of anybody that has looked at it, the difference between aged and fresh stuff fed to an electrostatic precipitator, either standard type of electrostatic precipitator or dry wall or wet wall or one of the charged droplet kinds of things that have been talked about here. But we don't know what differences there may be because we are talking about surface and it depends on the surface difference. So our objective again was to find something that might act, that we might find that there is a difference between the stuff that would hang onto and blind a collector, for example, which is not the subject today and the fresh stuff and the old stuff. We didn't know which would hang on differently. I know that in a General Motors paintcoating field there is a difference between material by their age and so on in the way it will hang onto the surface of the metal, or they prepare the metal. So these are among the reasons for investing some energy and time and thought in producing fresh small particles. Hopefully, in a predictable size range so that you can do some bench work, some pilot scale work and with enough quantity in the kilograms per hour and a half, kilograms per hour or per minute, it's only a factor of 60, so that you can do some decent work and control all of your conditions and have a predictable size spectrum going to your collector. It is a little hard to do on your models sticking out on the end of the field some place or up on the roof of a BOF furnace.

What we have done, the measurements we have had, our research grant, this work was done two and a half years ago. Our research grant started July 20th, three days after I had a call from TRW out on the West Coast, saying, "Can we have some samples and data." Can I tell the story? It is a free one. They had bought in a standard way some time, some money, some calendar time and some hours to produce a particle generating system. All of a sudden they found there wasn't any as all of you know. Bob (R. Hedden), for you--we will probably do our first firing up, we hope we are going to do some firing up with the new system, we are a generation ahead of where we were 2-1/2 years ago, we hope to fire it up tomorrow if the last nozzle was available to us and will be waiting for us at the Pittsburgh Airport tomorrow morning. Bob.

Hedden: I am going to start off after Professor Linsky has drilled into me the importance of particles size, a necessity for particles in a small micron, the diameter range. I went to work and relied on some of my experience as well as techniques and experience with electric furnace operation oxyacetylene cutting operations and put together a system including some of the principles involved in industrial operations. What I came up with was an arc which was initiated between a relatively nonconsumable tungsten electrode and a consumable feedstock of ordinary welding wires available in very large quantity of various diameters. There were several developmental experimental configurations I tried just to test out the basic principle. These are rather simplified drawings. The configuration on the one is just an off-the-shelf welding wire torch that was aimed at a tungsten electrode, in that case only 1/8 of an inch in diameter and without much difficulty I initiated an arc that produced voluminous quantities of finely divided iron oxide. The main difficulty there was the rapid melting of the tungsten electrode. It was not a very large difference in the areas of the wire and the area of the tungsten electrode so a large amount of heat was concentrated and although I was able to vaporize a portion of the welding wire, I also melted the tungsten electrode and for continuous systems this wouldn't do. I then went to a larger diameter tungsten electrode. In that case there wasn't any way to advance the tungsten electrode to compensate for wear either and also had some difficulty with the vertical orientation with the melted tungsten and some of the melted wire puddling up on a round peak deflection disc. By simply turning the whole apparatus 90° I eliminated a lot of the problems with the metal buildup. It started and had to wait for the wear of the tungsten electrode which was more than we had anticipated. I subsequently designed an apparatus so that I could advance the tungsten electrode. The electrode is oriented horizontally feeding into a 5 inch diameter pipe in a rectangular aluminum mounting box that holds the electrode assembly.

On the other side of the circuit a portion of the wire feed portion leads into the arc chamber. You could visually observe the arc and as you had to manually compensate for the tungsten erosion you also observed the gap between the electrodes. Near the center, the flexible hose leading to it leads to a ceramic nozzle inside the chamber which directs the helium in the arc region. That was an attempt to hold down oxidation on the tungsten electrode; however, I am not certain whether it actually accomplished the purpose of high velocity airstream through the chamber. The arc itself created a lot of turbulence in the area. It is doubtful whether the arc was adequately shielded or not. Due to space limitations we had to duct the gas stream up and bring it back down so we got an adequate number of diameters so we could smooth out the airflow and so forth for optimum sampling and that was subsequently exhausted to the atmosphere. I am sorry to say we didn't have any control system. We are sort of guilty of emission.

We used an Andersen sampler to get some particle size data and that was backed up by filters. It had a sample train and mass emission train in addition to the fractional size distribution of particulate matter.

I guess some of the most important things you would be interested in would be just how much fume this generated and what size range. As far as production rate went it has been calculated at over 1 hour period approximately 0.258 lbs of finely divided particulate matter would be produced. However, to produce that it took 5 lbs to approximately 5-1/2 lbs of welding wire. That gives a conversion ratio of about 4.75% and I am relatively confident that this is not the optimum conversion rate. No attempt was made in this rather limited research to optimize any of the parameters. Basically I was trying to determine whether a system could be made workable in order to maintain a relatively continuous manner.

That production rate I mentioned translated into some other values. I tried to give production figures in units that people may be working with. This is an average of 1.95 grams per minute generated and over an hour period they averaged a production rate of 117 grams. The average concentration was 670 milligrams per cubic meter. Between these variants, I ran three test runs to determine several things. One of the main items was to reproduce the ability of the system. I found an average of 30.08 grains per minute could be accomplished which is 1.95 grams per minute. At 1.95 grams per minute the standard deviation between the various runs was 0.0185 grams per minute. When I came to study a fractional breakdown of what was produced we used electron microscopes to make photographs and subsequently in true graduate student fashion I proceeded to count approximately 12,000 individual particles, counted the size which was quite a project in itself. This depicts frequency of distribution showing the size range and I have indicated the mean diameter. Something that presents a little different manner is probably this. The mean of the particles was 0.012 microns against standard deviation of 0.016 microns. The mass mean diameter was 0.017 microns.

Now the particles which were represented in this distribution are the discreet particles that were generated. As I guessed, some agglomeration and other combining forces would be involved. We had the Andersen stack sampler in this system and that was in there in an attempt to get the effective area in the dynamic size of the particles. Even with this I guess 77% of the particles were still less than 0.1 microns in diameter. I can't really speak for the significance of what really went on after the generation of the iron oxide.

That more or less brings us up to the present research we are starting to become involved in. In the new apparatus we are going to go to two consumable electrodes which will eliminate the problems of tungsten erosion, the potential contamination of tungsten particles in the exhaust gas stream and hopefully make it a more continuous system. There will be no need to manage or compensate for any electrode wear at all because of automatic, solid-state control of feed systems. The apparatus will be on approximately the same scale with approximate maximum contained flow past the arc area a nominal 100 cubic feet per minute. Another configuration that is going to be investigated in the research grant will be the use of two tungsten electrodes. The arc would be initiated between the two electrodes and be able to feed a conductive metal into the arc area, vaporize it and will have the capability of feeding nonconductive refractive materials and vaporizing and subsequently quenching them. It will be a much more flexible system than what we had in the past.

We are also going to take a much closer look at the particle size distribution and the effect of the various parameters such as current flow, the speed at which we quench the oxidized metals and what effect that has on particle birth and so forth. Hopefully we will be able to run some side comparison of various impactors which will be made available to us. I think that is about all I have to present. Are there any questions you may have?

: Bob, you mentioned the quenching process; can you describe that?

Hedden: I don't think I can really describe exactly what happens. I can only theorize what is going on with arc temperatures approximately 10,000°C, which vaporizes a portion of the feedstock material. The high volume of air flow past the arc area subsequently has a cooling or quenching effect and the vaporized iron which oxidizes at some point condenses into fine spherical particles. But I didn't really emphasize the particle shape but just about all the particles observed are spherical shaped which would indicate that at some stage they went from a vapor to a liquid state and subsequently solidified into a spherical configuration.

Linsky: All we are saying is quite observable. You might pass your own judgment. Part of the quenching may have come, and I am conjecturing, from the helium coming out of compressed gas and you get refrigeration as you decompress. But we don't know the mechanism. This work was done low budget as a matter of fact, with full credit to the Graduate Air Pollution Training Program of which Bob is a trainee. It was very low budget work and we borrowed and begged and stole everything we could get. And this is the result. Now we are getting a chance to use it in an exceptionally nice operation.

: Your original choice of the arc which is basically a fairly unstable device as opposed to something like high temperature furnace? Was it a matter of economy?

Hedden: Well, that was certainly one consideration. We had available to us a power supply and various pieces of standard welding equipment. When you say it is basically unstable, I guess everything is relative but we could control the voltage precisely. We could precisely control the feedback. The data indicates that it is a reproducible method notwithstanding the fact that the data is fairly limited.

Linsky: Let me explain, there are two points. That was one and we didn't think it was unstable because we knew about continuous feeding arc and when Bob first mentioned it my first thought was the kind that I had seen where you strike it and it is hard to maintain and so on. But this is fixed geometry and it is off-the-shelf as well, already off-the-shelf for fixed rather stable requested arc production. Another was that we didn't want to get into all of the problems of having a refractory and the additions of the refractory materials into the goop that we were trying to make. We knew that we wanted to get into brasses, into lead coil and to zinc and to all types, a wide range of conventional materials as well as the hope that we could do something in these other non-conductive materials of CM in one form or another that would be packed uniformly including coated rods or cored rods. Is that the question behind your question?

: Yes. What rate did you have to advance the tungsten electrode for compensation?

Hedden: It was about two tenths of an inch.

: You did this manually?

Hedden: It was a continuous compensation. That problem has been eliminated.

: What is going to be your output rate on this new gadget you are starting?

Hedden: That is a good question.

Linsky: The objective is what?

Hedden: I think we can make a tenth of an increase of what we have produced in the past. I don't think that is out of line. It is fairly conservative. We are talking about producing particles all less than a tenth of a micron in diameter which is quite a few particles.

Linsky: So that we will be up to realistic stack loadings from a BOF or something else or some other kind of a real life operation. In the sizes larger with a volume, total volume it would be diluted but it would be large enough to feed a decent sized laboratory scale unit.

: What are your chances of making something a tenth of 1 micron?

Linsky: The longer you keep the material in the hot zone the larger it will get. This has been well determined.

: In other words, this quenching appears to be kind of a compensation as it continues?

Linsky: In reduced compensation. Yes, I am sorry. I was talking about the factors involved in it. We think we can do it. I don't know of any reason why not.

: As large as 1 micron?

Linsky: I don't know of any reason why we can't because that has been done and it has been done for much larger particles, to produce much larger particles from plasma and similar operations where they were deliberately producing tonnage quantities. So I see no reason why we can't produce that by using the same fundamental technique they use to make sure that they get big ones and no powder.

: Could you run a larger arc?

Linsky: We might. It might be a larger arc. It might be a larger arc surface. It might be a larger electrode.

Hedden: That is one of the considerations we want to investigate.

Linsky: You have a hotter zone longer. I am sorry, a nuclei zone longer, a larger envelope of high temperature.

Hedden: There are also feed wires available that record. I think was mentioned in cores they contain previously reduced size material, powder material by varying the particle size of that material and it is also possible to have an effect on the output. You wouldn't possibly get the vaporization that was required in the solid wire. It would take advantage of this melting which would spherize the regular shape of powder.

: About the core materials, this is one big advantage that you have is that by using the outer shield of the electrode fill it with whatever you want, if you want to study other powders, some of the work that Davis had done prior to what he did on condensation was a simulated reactor problem using a filler of CO_2 and trying to remove that in case of reactorization problem.

: There is a whole wide range of all types of synergistic effects working in materials in cored wire. As I mentioned you even vaporized non-conductive materials. We were talking at lunch about vaporizing glass wire to approximate fly ash possibly. There are so many possibilities.

Panel Discussion No. 2

NEW CONCEPTS AND NOVEL DEVICES FOR FINE PARTICULATE CONTROL

Moderator J. H. Abbott (EPA)

Abbott: Before we open this meeting to questions on things that have been presented today, I would like to reopen a question I think was left kind of hanging yesterday. That question concerns charged droplet scrubbers. After most people had discussed and responded and discussed again, I came away with a distinct feeling that there were more cons than pros on the charged droplet scrubber side. And so I would like to pose a question. I think I will call on Mike Pilat first--that is "Why charged droplet scrubbers, if in fact they don't present any real advantages over standard electrostatic precipitators or wet wall precipitators?" Then I would like to give each one of those who were on the panel yesterday a chance to respond to whatever it is Mike presents here.

Pilat: I think one thing you have to realize here is that you can design an electrostatic precipitator or scrubber to have various collection efficiencies depending on, say in a precipitator, the number of fields and the plate spacing and so forth and so on. And so, assuming that our data being taken on this rather initial charged droplet modified study is reasonable, I would say that it appears feasible to achieve the same collection efficiency as presented by Grady (Nichols) I think it was or else it was Joe (McCain) on this 99.6% overall type efficiency on a very good installation. So this then reduces down to an economic situation which is more appropriate for emission based upon whether the gas is wet, whether you are willing to put up with entire capital cost for say a conventional dry precipitator versus lower capital costs and perhaps other more efficient cost on a scrubber; of course, a charged droplet scrubber is essentially just a scrubber.

: Do you see any advantages with respect to the particulate size, one versus the other?

Pilat: I think that the curves that, I forget who presented, I have mine nearly the same way he had. I think it came down to around 95 or 90% in the minimum. Hopefully we should be able to do that with the charged droplet scrubber. So let's say we have equivalent collection efficiencies. I don't think this is an issue on the charged droplet. So the advantages are not that this is some earth-shaking new device that gobbles up fine particles at a higher efficiency than large particles.

Abbott: O. K. Chuck, would you like to say a word?

Lear: Well, I think our device is a little bit unique from the rest of them and I am sorry that the impression was left as it was. I don't think it was a fair impression. I think that we are now competitive with electrostatic precipitators. We can probably reach the same collection efficiency and we can do so with less volume and less power. We can run with half the voltage of electrostatic precipitators. I am not sure what the current comparison is and my colleague back home, Walt Krieve, has told me he calculated volume reductions on the order of factors of 20. This looks good for a charged droplet scrubber in comparison with an electrostatic precipitator, not so much from improved efficiency perhaps, but a more economical operation. Our device does depend on relative velocity between droplets and particles. This is important to keep in mind and we depend on a high collision effectiveness probability to achieve a high efficiency . This can only be achieved by having a high field stream which means that you would have to keep the collecting electrodes in rather close to the spraying electrodes. As far as submicron work is concerned, I think it is still a bit of an open question where we expect different mechanisms rather than electrical impact scrubbing. We believe that the induced charging mechanism is going to be very important and I don't share the pessimism concerned with the evaporation process that might occur on droplets. I think that this still could also be an important process or mechanism for sub-micron particulate and I think it is simply a way of distributing space charges throughout the precipitator's volume much the same way that the corona wire might be. I think that it will still do it with less voltage and more efficiency and perhaps with better space charge distribution. It will certainly be a different space charge distribution, perhaps more efficient.

Abbott: Dr. Melcher, do you have any comment?

Melcher: Yes, it isn't as though we haven't discussed this after a year of warning. I pretty much endorse what Mike (Pilat) said. I can see no reason why charged droplet scrubbers should be any better for submicron than other devices unless it comes in processing the water collection or something like that. So the whole matter comes down to one of capital costs versus the operating costs in the particular application and we have got to view it that way. It certainly lends a great deal more flexibility to innovating in efficiency situation than we had before, where it was capital costs versus the dominant situation. And I think that really is incentive enough to look over it in my own opinion and with considerable enthusiasm.

Linsky. Could I take you back on that? Two points. One we are probably going to be looking at more and more heat recovery than we have done before because of the higher price of Btu and crude energy field prices. And this is going to precipitators as we have known. Will this kind of a device make a difference in comparison with the dry-plate electrostatic precipitator as we have known it? That is, what significance might we expect and I don't know? The second point I would like to bring out, I am sorry, the second question I would like to ask is how many of you are aware of or have known of liquids other than water to be recycled?

Pilat: I think we have just briefly done that. It gets to be a very difficult situation to find liquid other than water in our opinion.

Linsky: Have you looked at it? Do you have a report with a stream of materials that you have looked at?

Pilat: We have looked at a few things that possibly could be scrubbing liquid and looked at their vapor pressure and roughly contemplated doing a saturated stream of how much you are putting out in the stack and it gets to be quite large, even with low vapor pressure liquid.

Linsky: I combined this with the other because if we are going to be operating at lower temperatures because of better heat recovery because of the higher price of storeboughten Btu's, then this may change the, may change our temperature range for a large number of our conveying gases and therefore some liquids that might have been out of reason before because they couldn't take a 900°F burp will now be able to.

: There are a couple of reports out now on ESP work pursuing scrubbing mediums just per se for scrubbers. Of course, they could be conformed and put them in an electrostatic situation. That was done about three years ago. I can't remember who it was at the time.

Pilat: The report was on the scrubbing range.

: It was the SO_2 scrubber.

: Right, but I mean as they investigated the other they should have some of the parameters involved as far as vapor pressure.

Linsky: Good. I hate to have the students do busy work. They have got a lot more things that they have fun with. There was one other point and that is, that we are going to be talking about the 95, 97, 99% small particle control that we haven't even begun to talk about yet. And that is the next generation where the best equipment that is on board now is the primary collector or the precleaner and there isn't any, I don't think there is very much, question that it is going to have to be done. And whether we do the conversion of some of our exhaust gases in the stack in one way or another, but certainly we are not going to be letting the atmosphere do it, continue to do it as it has been in the past from power plants, for example, which are now putting out even with a good collector, putting out about ten times as much per hour as any cement plant is allowed to put, 40 lb an hour load.

: We look forward to the time when we will have control of very fine particulates up into the 90% range.

: I think that according to what Mike (Pilat) and Jim (Melcher) said over here that you have a fairly good way to compare an electrostatic with your charged droplet scrubber. Fundamentally your droplet scrubber has a field, an electric field that drops off as 1 over R square and your electrostatic has one that falls off as 1 over R. Therefore at the point of interaction you will have a smaller electrical force that must be compensated for by surface area. But it is very easy to get that surface area with your droplets and it certainly offers enough promise. You should continue following that line as a source of removing these fine particles so you can get the distance that you must transport them to a droplet is much less than the distance to a collection electrode. You can have a droplet in the near vicinity that will influence that region. So it is an area of promise and I think it should be followed.

Abbott: Anyone else who was on the panel yesterday have a comment?

: I would just like to say that with my present enlightened viewpoint what we are really doing is enhancing the collection of the scrubber. If you have a field situation where you would ordinarily use a scrubber, if it would additionally collect all of the particles, not just the small particles. I think that would be a real development and I think that is still a possibility. It will never replace the electrostatic precipitator but it surely would enhance the scrubber.

Abbott: Dr. Penney.

Penney: Well, of course I have thought about this for many years. I guess I never, I surely have never had the chance to go into it in depth the way

Dr. Melcher has. But I think I came up with a similar conclusion. I expect that I couldn't see that it was any new breakthrough. And one other handicap, I always think with a new device it also seems to me that you are going to use the old device unless the new device is distinctly better. That is, it is hard to get a new device adopted unless it has real advantages because you have a lot of experience back of the old one. And so I came down to the feeling that the biggest hope for the charged droplet was some special application where you wanted water for some other purpose rather than feeling it will supplant the electrostatic precipitator. And I have never been quite sure what that other application was.

Linsky: But if we are getting down to the dew point because of better heat recovery?

Penney: Ah, then you have got advantages for the precipitator too.

Linsky: No, I mean down at the lower end. We are getting at the dew point, then you are better off with a wet system.

Penney: If you are going to run the electrodes wet, you mean. Well, I don't know.

Linsky: I haven't thought it through either.

Melcher: If there is within the realm of deposit problem the charged particles collecting around, the possibility of a breakthrough has to be made clear to explain, in my opinion only for making a large area available for collection compared to what is available in the precipitator. I think that is the direction can be pressed to really make this breakthrough and a much shorter residence time.

Abbott: Well, we have pretty well, reopened and rehashed that one. I will give anybody one last chance to make a comment. If not, we will close that one for the time being anyway.

I think what we should do now is confine our comments and questions to members of this panel based on presentations that we have heard this morning. And I think to begin with I will, and incidentally, panel members feel free to question other panel members please. I will just throw the questioning open to everyone including panel members and see what comes of it.

: I would like to comment on ESP collection. I have taken a position that the Deutsch equation is one that will not realistically describe the performance of an electrostatic precipitator. Like Grady (Nichols), we have developed a theory and outlined a calculational procedure and programmed this with a computer and we have generated results of collection efficiency which are in disagreement with those predicted by the Deutsch equation and in reasonable agreement with the limited data that we have been able to put out, that we have been able to obtain in the literature. Without going into any great detail about our mileage, we have basically assumed that the particles followed a determined path and have developed a determinant model as opposed to the Deutsch equation which is a suggested model. And the reason that we used that approach is simply that on a mass basis you have something like 99.+, something in excess of 99% of particles in an aerosol which will follow a deterministic path and vast improvements take place.

: Our submicron particles are in fact remixed rather well although there is some evidence that there is a concentration gradient developed across the precipitator as you proceed down. If you scan across the inlet duct to the precipitator with a laser and a detector you will find uniform particle size distribution, but as you proceed downstream before we look at this thing, a pair of plates with a wire down the middle and we look at it now lasered which would be sensitive to the finer particles because this is where the scattering occurs you will find a gradient that tends to come up suggesting the possibility that turbulence exists in the inter-electrode space, that is somehow down near the region so that you would have a transport toward the plate rather than away from the plate. Now what would be the consequences of this? The original Deutsch equation says that we will assume a uniform particle size distribution and we will collect those materials, those particles that are contained within some boundary region adjacent to the plate and we will say that our efficiency could be associated with the probability of a particle being in here as opposed to out here. If we pump this up a hair with the concentration gradient at the wall what it has done is improved the collection efficiency so that our old happy Deutsch equation that we run into gets to be 1 minus exponential and that gets to be A over B times W. Now you have to modify that W with a little factor q which has to do with the ratio of concentration adjacent to the plates opposed to what it is in the average conditions across the plate. Now that would lead to an increase in collection efficiency which would just move the precipitator plate just a hair better in there. Now, if we see this developing from a uniform distribution at the inlet until you proceed to the other end you will have to do some shenanigans to protect this development of this concentration gradient into account. But every evidence that we have where we have been able to measure the particle size distribution we have been able to calculate the efficiency as a function of size distribution and check this with a reasonably good precipitator in the field. I have to say that we have gotten what I consider to be very good agreement between the prediction and the measured performance.

: Are you saying that the given particle size can convey the Deutsch equation?

Nichols: Any particle that you know the migration velocity we expect and every evidence we have here that it does in fact follow this.

: But then if you take a mixture of two sizes you have got two exponentials.

Nichols: True. And the way we handle this, coming into the inlets we have a particle size distribution break this up into small increments and break it into a number of individual and discrete particle sizes and handle each one individually. Handle it as a given particle size. Calculate the charge on it and its resultant migration velocity and individually handle these particle sizes as they proceed through the precipitator.

: So you have got to sum a lot of individual exponentials.

Nichols: Sum the result of individual exponentials.

: So you won't be applying the Deutsch equation to the overall.

Nichols: No! You apply it only to a very narrow particle size range. Now applying the Deutsch blindly and assume you are dealing with something like a mass medium diameter is wrong, wrong, wrong. You can't make a worse mistake than that.

: I'll buy that. I think the approach you have just indicated is a step in the right direction. Getting back to what we proposed, we want that type of calculation using the Deutsch Andersen equation that is exactly what I was talking about. Breaking it up into size fractions and calculating the efficiency, the efficiency associated with that size range and multiplying it by the weight fraction associated with that range, which is what you just indicated. We get substantial disagreement beteen the two theories, the Deutsch theory and what we got.

: Again, as I understand it and I am under the theory.

: From what you have said, first of all I think the experimental effort in the literature indicated that most of the particles do in fact follow deterministic paths.

: I am not saying that what you have done is wrong or what other people have done is wrong because equipment is being built today and companies are making money and the approach that they are taking treats W as a parameter in the model and adjusts the value of W to bring whatever experimental data they have, rather to bring the Deutsch model more in line with whatever experimental data they have available.

Nichols: Now I don't agree with that either.

: Well, that is basically what industry has done.

Nichols: We take issue with that first on.

: The problem with that is when you take those results and you try to extend them or extrapolate them to new aerosol systems or new operating conditions you find the equation breaks down.

Nichols: It is incorrectly used.

: Everybody agrees with that. The point that I make I think that the basic reason this is filled, this approach has not worked is the Deutsch equation to repeat myself again, the Deutsch equation does not realistically describe the performance of a precipitator. It does not describe what is actually happening within the unit. If you have got 90% or if you say it is closer to 99% particles following a deterministic path, then I think the most reasonable approach is to use a model that assumes that.

Nichols: Let's have a size distribution first before you make that statement.

: What I was going to agree is that it seemed to me that this would really be quite a straightforward problem if you assume that the flow through there was going to follow something like the universal velocity profile, calculate a viscosity from that velocity profile. Then superimpose your migration velocity on that and solve it just like you would the transportation moving problem. That may be quite a straightforward solution.

: Not that straightforward, because again you are applying what is valid for a one-phase system to a two-phase system.

Nichols: Well, that is true but in your larger particles you would be somewhat in error or you can superimpose the correction term on here.

: That is correct, but it is the feedback that contributes to this collection efficiency that we all do.

: That is a thing that you can take a baseball bat, a glove and a couple of good teams and stick them in the stack and catch.

: I agree that if you are talking about fine particles, very fine particles that the Deutsch equation is the right approach.

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Non-metric	Multiplied by:	Yields metric
Btu	252.00	cal
°F	5/9(°F-32)	°C
ft	30.48	cm
ft^3	28.32	liter
gal.	3.79	liter
HP	746	W
in.	2.54	cm
$in.^2$	6.45	cm^2
lb	0.45	kg
$lb/in.^2$	0.07	kg/cm^2